
Environmental drivers of earthen heritage deterioration in dryland regions

Jennifer Claire Jones Richards

Supervisors: Heather Viles,
Richard Bailey and Jerome Mayaud

St Cross College
Oxford University

Thesis submitted for the degree of
Doctor of Philosophy in
Science and Engineering in Arts Heritage and Archaeology

Trinity Term 2020

Abstract

Earthen sites form a key part of our heritage: providing us with evidence for past civilisations, acting as a focal point for community identity and forming aesthetically pleasing buildings and structures. These sites are found on every continent but are concentrated in dryland regions, such as across northwest China and central Asia. Due to the low durability of earthen materials, many earthen heritage sites exposed to harsh dryland environments are experiencing extensive deterioration. If we are to pass on these sites to future generations, we need to understand how earthen heritage sites are impacted by environmental drivers of deterioration and how the risk of deterioration could be minimised. To address this challenge, this thesis determines the likely impacts of the main environmental drivers of earthen heritage deterioration under current and future conditions in dryland regions.

The research presented in this thesis examines the impact of wind and rain as drivers of deterioration at Suoyang Ancient City. Suoyang is an archaeological city built out of rammed earth in the Han (206 BC–220 AD) and Tang (618 – 907 AD) dynasties and is located in Gansu Province, northwest China, on the ancient Silk Road. It exhibits a range of deterioration features from the detachment of surface material to wall slumps and collapses. In 2015, an experimental area was established at the site, which includes several test walls.

This thesis uses a combined fieldwork-modelling approach. A controlled field experiment was used to investigate the deteriorative impact of key individual environmental processes on earthen structures. Geomorphological signatures were used to assess the relative importance of wind and rain as drivers of deterioration. These field results were used to develop and parameterise the Vegetation and Sediment TrAnsport model for Heritage Deterioration (ViSTA-HD), a cellular automaton model that spatially resolves the risk of environmental driven deterioration across earthen heritage wall faces. ViSTA-HD was used to test the impact of future climatic and conservation scenarios on the risk of earthen heritage deterioration.

Findings showed that even though individual wind events are of low magnitude, their high frequency occurrence results in a significant cumulative impact of wind-driven deterioration under both current and potential future conditions. Increasing natural vegetation cover was found to minimise the risk of deterioration under a range of climatic scenarios.

Given the similarities in material properties, history and location of Suoyang to other earthen heritage sites in Northwest China and central Asia, findings in this thesis can be applied to many other earthen sites in these regions.

Acknowledgements

I could not have produced this thesis without the support of my supervisors Heather Viles, Richard Bailey and Jerome Mayaud. I feel exceptionally privileged to have been supported by a team from whom I have learnt so much. From developing research methods to model testing to paper writing, I am eternally grateful to the time and effort they have spent encouraging and critiquing my work. Thank you all so much.

This research was made possible by funding provided by the UK Engineering and Physical Sciences Research Council (EPSRC) through the Science and Engineering in Arts Heritage and Archaeology (SEAHA) Centre for Doctoral Training and the Getty Trust. It has enabled me to undertake research both in the UK and China, attend conferences to disseminate key findings and purchase research resources.

I would like to wholeheartedly thank the Getty Conservation Institute and the Dunhuang Academy for their continued support throughout my DPhil. I am honoured to have worked with institutions at the forefront of heritage research. I would like to thank Xudong Wang and Tom Learner for making this collaboration possible. I would also like to thank all those from both institutions who have helped shape my research including: Qinglin Guo, and Qiangqiang Pei for their advice on earthen heritage research and ongoing support; Fasi Wu, Guojing Zhao, Hongtao Zhan for their help in designing and analysing field experiments; Dongpeng He, Fei Qiu, Jingjing Huang, Guojing Zhao, Bo Zhang and Wei He for their time and effort in collecting field data at Suoyang; and Alick Leslie, Simeon Wilkie, Beril Bicer-Simsir and Davide Gulotta for providing useful and thought provoking feedback on my research.

I am grateful to have been part of OxRBL and CoHeSys who have been a constant source of knowledge and friendship throughout my DPhil. I have learnt so much from all members who I have been lucky enough for my time to coincide with. In particular, I would like to thank Hong Zhang whose tireless enthusiasm and organisation meant I managed to collect all my field data with a day to spare; is the most efficient translator of documents; and seemingly can get anyone in China to respond within an hour. I have also learnt so much from OxRBL's visiting researchers. I am so pleased to have had to opportunity to learn from Linyi Zhao, Faguo He and Shanlong Wang and will not forget the laughter filled hours Linyi and Faguo spent with me practising my attempts to learn Mandarin.

Finally, I would like to thank my friends, family and teachers who have inspired and supported my love of finding out new things. My interest in physical geography research has been shaped, in particular, by Abi Stone and John Tibby – thank you for helping me develop as a geographer and researcher. My DPhil journey started dancing round my Grandma's sitting room on receiving my offer. Since then I have had gallons of tea discussing the value of heritage with Jedhi and my parents and sister, Nathalie, have (valiantly) listened to hours of earthen heritage chatter. I cannot begin to thank my parents, encouraging me to pursue what I enjoy and picking up the pieces when things haven't gone to plan (and of course for all your proof reading...). And lastly, I will forever be grateful to Tom, for being endlessly supportive throughout this whole process.

非常感谢你



Table of Contents

Abstract	iii
Acknowledgements	iv
Table of Contents	vi
List of Figures	xi
List of Tables	xviii
Section 1: Research Context and Design.....	1
1 Introduction	2
1.1 Heritage, value and the environment	2
1.2 Earthen heritage	4
1.3 Overview of thesis	6
2 Earthen heritage research: Past, present, future	9
2.1 Earthen Heritage.....	9
2.1.1 Earthen heritage research	11
2.2 Rammed Earth	16
2.2.1 Construction and material properties	16
2.2.2 Rammed earth sites.....	17
2.3 Deterioration processes	18
2.3.1 Rain	21
2.3.2 Wind and sediment transport	22
2.3.3 Variations and interactions between drivers of deterioration	22
2.4 Conservation approaches	24
2.4.1 Conservation practices in China	27
2.5 Cultural similarities in approaches to earthen heritage conservation.....	29
2.6 Earthen heritage research challenges	31
2.6.1 Laboratory methods	34
2.6.2 Field-based methods	35
2.6.3 Modelling.....	38
2.7 Aim and objectives	40
3 Research framework and methods	42
3.1 Overarching framework.....	42
3.2 Field site: Suoyang Ancient City.....	45
3.2.1 Experimental area.....	52

3.2.2	Site visits	55
3.3	Field-based methods	56
3.4	Modelling.....	57
Section 2: Environmental drivers of earthen heritage deterioration		59
4	A controlled field experiment to investigate the deterioration of earthen heritage by wind and rain (Paper 1).....	61
4.1	Introduction	62
4.2	Methods.....	64
4.2.1	Site description	64
4.2.2	Environmental conditions	67
4.2.3	Experimental design	67
4.2.4	Test wall preparation.....	70
4.2.5	Deterioration test	72
4.2.6	Data analysis	76
4.3	Results.....	76
4.4	Discussion	80
4.5	Conclusion	87
4.6	Chapter 4: Summary and implications	89
5	The importance of wind as a driver of earthen heritage deterioration in dryland environments (Paper 2)	90
5.1	Introduction	91
5.2	Material and methods	94
5.2.1	Study site: Suoyang Ancient City	94
5.2.2	Approach	98
5.3	Results.....	102
5.3.1	Small test wall.....	102
5.3.2	Large test walls	105
5.3.3	Historic walls.....	107
5.4	Discussion	111
5.4.1	Nature and distribution of deterioration	113
5.4.2	Magnitude and frequency of deterioration processes	117
5.4.3	Persistence of deterioration features	117
5.4.4	The importance of wind as a driver of deterioration	119
5.5	Conclusion	121

5.6	Chapter 5: Summary and implications	122
Section 3: Earthen heritage deterioration under future conservation and climatic scenarios		123
6	Modelling the risk of deterioration at earthen heritage sites in drylands (Paper 3)	125
6.1	Introduction	126
6.2	Data collection	130
6.2.1	Field site	130
6.2.2	Wind	131
6.3	Sediment transport	134
6.3.1	Vegetation	135
6.3.2	Average climatic conditions	136
6.3.3	Deterioration data	137
6.4	Model Description	137
6.4.1	Environmental module	138
6.4.2	Deterioration module	144
6.5	Sensitivity testing of ViSTA-HD	152
6.6	Model validation	157
6.6.1	Formation of deterioration features	157
6.6.2	Simulating deterioration in different environments	158
6.7	Applications of ViSTA-HD	161
6.8	Conclusion	162
6.9	Chapter 6: Summary and implications	164
7	Deterioration risk of dryland earthen heritage sites facing future climatic uncertainty (Paper 4)	165
7.1	Earthen heritage: a complex conservation problem	166
7.2	Modelling deterioration risk	167
7.3	Deterioration under future climate scenarios	172
7.4	Effectiveness of nature-based conservation strategies	176
7.5	A research-driven future for earthen heritage	180
7.6	Methods: ViSTA-HD Model	180
7.6.1	Environmental module	181
7.6.2	Deterioration module	182
7.6.3	Model runs	182
7.6.4	Input conditions	183

7.6.5	Model implementation.....	183
7.6.6	Model considerations	184
7.7	Chapter 7: Summary and implications	185
Section 4: Discussion and conclusions		186
8	Discussion and conclusions	187
8.1	Thesis objectives.....	187
8.2	Cross-cutting themes.....	190
8.3	Theme 1: Suitability of methods used in earthen heritage research.....	190
8.3.1	Methods assessing individual and multiple drivers of deterioration.....	191
8.3.2	Methods assessing past, present and future deterioration	195
8.3.3	Application at earthen heritage sites	197
8.3.4	Multi-method approach	199
8.4	Theme 2: Drivers of earthen heritage deterioration.....	200
8.4.1	The importance of wind as a driver of earthen heritage deterioration.....	200
8.4.2	Other drivers of earthen heritage deterioration.....	201
8.5	Theme 3: Applicability of findings to other earthen sites	205
8.5.1	Material properties.....	205
8.5.2	History.....	207
8.5.3	Climatic conditions	209
8.6	Theme 4: Future deterioration and potential conservation	210
8.6.1	Climatic impact	212
8.6.2	Conservation impact.....	213
8.7	Original contributions of this research.....	217
8.7.1	Understanding environmental drivers of deterioration at earthen heritage sites.....	217
8.7.2	The development of field approaches to assess deterioration processes....	218
8.7.3	The development of a cellular automata model for predicting the risk of earthen heritage deterioration	218
8.7.4	Evidence based recommendations for nature-based conservation at earthen heritage sites	219
8.7.5	Wider application of research approach	219
8.8	Implications for conservation practice	220
8.9	Future work	221
8.10	Conclusions.....	223

References	225
Appendices	273
Appendix A: Author contribution	274
Appendix B: Earthen heritage value and conservation approach	276
Appendix C: Supporting Information for Paper 3 (Chapter 6)	307
Appendix D: Supplementary Material for Paper 4 (Chapter 7)	332
Appendix E: Glossary and Atlas	341

List of Figures

Figure 1.1: Thesis structure comprised of four overarching sections and eight chapters ..	8
Figure 2.1: The distribution of earthen world heritage listings a) in dryland regions. As one world heritage listing can be comprised of many heritage sites, b) shows the distribution of earthen sites that comprise the Silk Roads world heritage listing (represented by only one dot in panel a). Maps were created by the author, adapting figures from <i>Thomas (2011) and WHEAP (2012)</i>	10
Figure 2.2: Key factors for developing effective conservation strategies.	14
Figure 2.3: Schematics of earthen heritage deterioration driven by (a) wind, (b) rain and (c) solar insolation and temperature. The dotted arrows indicate the movement of particles.....	19
Figure 2.4: The test wall construction process: a) setting the forms, b) layering the soil, c) ramming the soil layer, d) the finished wall. Photo credits: Dunhuang Academy.	37
Figure 2.5: Examples of outputs from cellular automaton models: a) showing the development of nebkha dunes and b) showing the development of braided rivers. Images are adapted from Mayaud et al. (2017) and Murray and Paola (1994), respectively.	40
Figure 3.1: Research framework used in this thesis	44
Figure 3.2: The site of Suoyang Ancient City. Its location: a) in the Hexi Corridor northwest China; and b) to the west of an alluvial fan forming to the north of the Quilian Mountains (credit: Google Earth). The Inner City walls are shown in c) and d) a sketch map shows the key wall and irrigation features (provided by the Dunhuang Academy). 46	
Figure 3.3: A geological map of the area around Suoyang. Adapted from Wang et al., (2016).	47
Figure 3.4: a) An aerial view of Suoyang (credit: Dunhuang Academy), b) the Buddhist monastery located northeast of the inner city walls, c) a section of the southern inner city wall with fortress tower and d) a heavily deteriorated section of the east inner city.	48
Figure 3.5: The dominant vegetation species found at Suoyang. Credit: Dunhuang Academy.	50
Figure 3.6: Mean monthly maximum and minimum temperatures (°C) and mean monthly rainfall (mm) for Guazhou county. Climatic data (unpublished) was provided by the Dunhuang Academy for the period 1997-2007 (temperature) and 1995-2005 (rainfall).	50
Figure 3.7: The tests walls located at Suoyang in the experimental area. a) The small test wall with the section of the test wall used in this research indicated with a red arrow and b) the large test walls.....	53
Figure 3.8: Summary of methods used in this thesis to address earthen heritage deterioration.....	56

Figure 4.1: A site map of Suoyang showing the location of the inner and outer city walls, cross bow platforms, monastery, wind erosion platform and experimental test area. Inset is the location of Suoyang within China. Photos show a) the Buddhist monastery, b) a gully, c) part of the east inner city wall that has deteriorated into distinct sections, d) the detachment of a section of the southern inner city wall and e) a crack in the southern inner city wall. The location of photos a) – e) at Suoyang are indicated in grey boxes on the site map.....	66
Figure 4.2: Texture maps showing the surface topography after initial surface preparation and before the first set of experimental runs of a) test area A, b) test area B, c) test area C and d) the location of the test area on the test wall at Suoyang. Light blue indicates raised areas and dark blue indicates lower areas. Maps in panels a) to c) were produced at the Dunhuang Academy using the software licensed for use only in China. 71	71
Figure 4.3: The test setup of a) the Portable Wind Erosion Simulation Device and b) the Portable Rain Erosion Simulation Device in front of Test Area C on the test wall. All measurements are in centimetres.....	74
Figure 4.4: Deterioration caused by a -c) wind, d-f) sediment-laden wind and g-i) rain with i) visual observations (Obs.) while the deterioration test was undertaken, ii) post-test photographs of the test area and iii) the laser scanning deviation map showing changes in surface topography (blue = negative surface change, green = no significant change and yellow = positive surface change), note the difference in the quantitative scale between rows (mm). The letter (A), (B) or (C) refers to the test area the experiment was undertaken on.	78
Figure 4.5: Examples of deterioration features at Suoyang: a) pitting, b) an incipient gully (see Figure 4.1b for a developed gully) and c) wind polishing.	81
Figure 4.6: A conceptual diagram showing the frequency and magnitude of environmental conditions and their associated features on earthen heritage deterioration at Suoyang. The solid crosses show the range of frequencies and magnitudes over which clean wind, sediment laden wind and rain currently operate. The potential impact of future environmental conditions is shown with a dashed cross.....	86
Figure 5.1: The site of Suoyang Ancient City a) from above (Credit: Google Earth) and b) the monastery (Credit: author's photo).	95
Figure 5.2: A plan view of Suoyang showing the location of the small test wall, large test walls and inner city walls. Sites for expert deterioration survey assessment on the inner city walls are indicated.	97
Figure 5.3: Our approach for assessing geomorphological signatures through the formation of deterioration features	98
Figure 5.4: Deviation maps showing change in surface topography (mm) after being exposed to a) wind, b) sediment laden wind and c) rain. Note the different scales for each deviation map. Adapted with permission from Richards et al. (2019b).	104
Figure 5.5: Deterioration features found on the large test walls after one year exposed to the environment at Suoyang: a) scouring around the base of the test walls, b) the rounding of the test wall corners, c) the variation in flaking on the eastern side of Wall 1	

and d) the deposited material at the base of the west side of Wall 1, much of which was deposited after a 36 hour storm event.	106
Figure 5.6: Deterioration around Suoyang at the a) East, b) Bisecting, c) West, d) North and e) South inner city wall. Deterioration on the east or internal wall face is shown in (i) and west or external wall face is shown in (ii).....	108
Figure 5.7: A schematic of the surface coverage of wind- and rain-driven features over time. The cumulative impact of these features is shown with a dotted line.	120
Figure 6.1: Suoyang Ancient City. a) An aerial view showing the layout of the inner city walls with location of Suoyang in China inset (Credit: Google Earth) and the deterioration features found the site of a) polishing, b) pitting and d) slurry.....	132
Figure 6.2: Plan view of a) the test walls and b) the vegetation transects where h is the height of the element. Along the transects, measurements were taken using individual anemometers (circle), wind towers (triangle) and sediment traps (diamond). Photos of the equipment used and the experimental set up are presented in the bottom panel.	133
Figure 6.3: A schematic diagram of ViSTA-HD showing the processes occurring in the environmental and deterioration risk modules.....	138
Figure 6.4: The sediment deposition pathway in front of the wall face and the wind velocity recovery in the lee of the wall for a) wind perpendicular to the wall, b) wind at an acute angle to the wall.....	142
Figure 6.5: The process for determining the overall risk of deterioration given standard a) environmental, b) spatial and c) temporal conditions. Examples of risk calculations are shown in d) and e). The risk of pitting in a polled cell for a single iteration is shown in d) and the overall deterioration given the risks of pitting, polishing and slurry in a polled cell after four iterations is show in e). See section 6.4.2 for how standard conditions were determined. Pi = Pitting, Po = Polishing and S=Slurry.	146
Figure 6.6: The probabilities used in the sensitivity testing for a) environmental risk scenarios uniform, low and high, b) spatial risk scenarios none (no impact), low and high, and c) temporal risk scenarios none (no impact), low and high	155
Figure 6.7: The mean risk of deterioration after 50 model runs when inputted a) uniform, b) low and c) high environmental conditions and subjected to varying spatial and temporal risks (ER, SR and TR, respectively – see Figure 6.6 for definitions of uniform, none, low and high). Hatching indicates areas of the wall where the standard deviation is < 5% of the mean. Note the different scales used for ER uniform, compared to ER low and high	156
Figure 6.8: The overall deterioration risk in each cell across the wall face for different a) environmental, b) spatial and c) temporal risks (ER, SR and TR, respectively). The areas in b) and c) shaded with grey indicate results from the unrealistic uniform environmental risk scenario and thus should only be considered with regards to saturation of the deterioration risk scale. See text for further discussion.....	157
Figure 6.9: a) The maximal height of sand across all model runs ($n=50$) and the mean ($n=50$) risk of b) polishing, c) pitting, d) slurry and e) overall deterioration on a wall face from 50 replicate runs inputted with conditions representative of those at Suoyang.	

Note the different scales for each deterioration feature; 0= very low risk, 1= very high risk. Examples of b-i) polishing, c-i) pitting and d-i) slurry at Suoyang are shown. 159

Figure 6.10: Overall risk of deterioration caused by wind and rain a) as determined by conditions recorded by the weather station and for locations b) sheltered from the wind and rain, c) exposed to the wind and sheltered from the rain, d) sheltered from the wind and exposed to the rain and e) exposed to the wind and rain. Photos of deterioration from around Suoyang, representative of the respective conditions modelled are shown (a-i to e-i). Here, sheltered locations are modelled with a mean wind velocity of 5 ms^{-1} and the median rainfall event being 1 mm with an interquartile range of 1.75 mm. Exposed locations modelled with an average wind velocity of 12 ms^{-1} and the median rainfall event being 3 mm with an interquartile range of 8 mm. 160

Figure 7.1: The site of Suoyang Ancient City (a-c), a plan view of the initial model setup (d) and the three major deterioration features (e)-(g). 169

Figure 7.2: The overall risk of deterioration after 100 years under: (a) current climatic conditions; (b-i) different climatic changes; and (j-m) different conservation strategies. In panels b-m, deviations from the control results are shown with red and blue, indicating an increased and decreased risk of deterioration, respectively. 173

Figure 7.3: The deterioration risk and difference in deterioration risk for polishing, pitting, slurry and the overall deterioration after 100 years of model time, under (a-c) a regime of low mean annual wind velocity and rainfall, and (d-f) a regime of high wind velocity and rainfall. Different conservation strategies were applied: (a, d) no conservation strategy (control); (b, e) addition of a windbreak; and (c, f) 80 % vegetation cover. 179

Figure 8.1: A schematic showing how the themes discussed in this section of the thesis cross-cut with the thesis objectives. 188

Figure 8.2: Test Wall 1 post construction and after being exposed to the environment for 1 year and 2.5 years. Features present on the wall after 2.5 years that are similar to those produced in the controlled field experiment in Chapter 4 (Paper 1) are highlighted. Photo credit: Dunhuang Academy. 192

Figure 8.3: The Multi-field Coupling Laboratory at Dunhuang Academy. a) The lab building, b) the Summer test Chamber, c) the Winter test chamber and d) the wind and rain chamber. Photo Credit: Dunhuang Academy. 195

Figure 8.4: (a) Properties of historic material at Suoyang and a selection of earthen heritage sites in northwest China with (b-d) illustrating the dry density, porosity and water content, respectively. The dark pink areas show the range in material properties recorded at Suoyang with the light pink areas showing +/- 50% of Suoyang's range. 206

Figure 8.5: A comparison of historic context of Suoyang to other earthen heritage sites in northwest China and central Asia with regard to a) the main period of construction and use and b) contemporary reported conservation strategies. 208

Figure 8.6: The likely importance of wind and rain as drivers of earthen heritage deterioration at sites which form the Silk Roads World Heritage listing, located over a spectrum of dryland climates from dry subhumid to arid. Photo Credits UNSECO (2014). 211

Figure 8.7: A schematic showing a four-stage approach to assessing the relative benefits and trade-offs when implementing conservation strategies.	214
Figure C.1: Wind velocity recorded at Suoyang between September 2015 and August 2016, grouped into four seasons.	308
Figure C.2: The relationship between porosity and a) the mean normalized minimum wind velocity, and b) the b coefficient using the joint Kalahari-Suoyang dataset.	310
Figure C.3: a) The relationship between wind direction and relative wind velocity at two locations shown in b). The relative wind velocity is calculated according to the wind velocity at 1 h upwind of the wall (where h is the height of the wall).	311
Figure C.4: A photograph of the flare experiment showing the deflection of the wind flow around the test wall.	312
Figure C.5: a) The interaction of the environmental and deterioration modules at the wall face: x_1 and x_2 represent environmental conditions resolved in the environmental module. The solid black arrows show interpolation between inputs. Dashed vertical arrows indicate the extrapolation of conditions above and below the environmental input and the dashed horizontal arrows indicate the interpolation between calculated conditions across the wall face. b) An example of wind velocity inputs from the environmental module into the deterioration module.	313
Figure C.6: Change in a) wind velocity (relative to the wind velocity 0.5 m above the ground), and b) total volume of transported sediment, with increasing height from the ground. The dashed black line in b) indicates the determined height for sediment transport occurring within and above the saltation zone.	315
Figure C.7: Wind roses comparing the wind regime above 4 ms ⁻¹ at Suoyang to the wind velocities inputted into ViSTA-HD.	318
Figure C.8: a) Total rainfall, b) quantity of rainfall in each storm event, and c) the number of rain events per iteration, over an annual time period and for each season (DJF, MAM, JJA, SON) individually. The dashed black lines in the first panel show the mean annual rainfall and the solid black lines shown the minimum and maximum annual rainfall.	319
Figure C.9: A comparison of the modelled wind flow around three walls of different heights (3, 5 and 8 m) with data collected from Suoyang: a) Location and heights of the three modelled walls; b) wind velocity across the model space caused by a wind blowing from left to right; c) transects of wind velocity to the side of the wall where acceleration occurs and through the centre of the wall; d) comparison of modelled wind velocities (grey) to wind velocities collected at Suoyang (black). The distance from wall is reported in h (where h is the height of the wall), to enable comparison between model and field data. Error bars show one standard deviation from the mean.	321
Figure C.10: The development of dunes in front of two walls (measuring 50 m and 10 m in length and 6 m in height), over 300 iterations.	322
Figure C.11: Comparison of modelled and real dune morphologies on the upwind side of walls. The range of dunes morphologies are shown using histograms for the modelled dunes and triangles for the measurements taken in the field. Four model configurations were used to compare a) the height of exposed walls and c) the dune length. An	

example of each model configuration after 500 iterations is shown in b). The model set up is shown in d).	324
Figure C.12: Comparison of dune morphologies between models starting with a uniform (flat) sand height and a pre-conditioned surface for a) dune length and b) exposed wall where h is the height of the wall.	326
Figure C.13: The impact of rain on a) test wall 24 hours after a storm event, and b) on the historic walls	327
Figure C.14: The running mean for 50 repeat runs of the a) mean and standard deviation of the risk of deterioration across two wall faces and b) the standard deviation of the risk of deterioration in randomly selected individual cells. The approximate location of the individual cells are shown on wall 1.	329
Figure C.15: Overall risk of deterioration modelled at 2 cm resolution on walls representing walls in locations a) sheltered from the prevailing wind and sheltered from rainfall, b) exposed to the prevailing wind and sheltered from rainfall, c) sheltered from the prevailing wind and exposed to rainfall and d) exposed to the prevailing wind and exposed to rainfall. Here, sheltered locations are modelled with a mean wind velocity of 5 ms^{-1} and the median rainfall event being 1 mm with an interquartile range of 1.75 mm. Exposed locations modelled with an average wind velocity of 12 ms^{-1} and the median rainfall event being 3 mm with an interquartile range of 8 mm.	330
Figure D.1: The risk of polishing, pitting, slurry and overall deterioration after 100 years of model time on a 10 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 1 ms^{-1} decrease, (c) 2 ms^{-1} increase and (d) 5 ms^{-1} increase, in mean annual wind velocity. .	332
Figure D.2: The risk of polishing, pitting, slurry and overall deterioration after 100 years of model time on a 10 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 10% decrease, (c) 20% increase and (d) 50% increase in mean annual rainfall.....	333
Figure D.3: The risk of polishing, pitting, slurry and overall deterioration after 100 years of model time on a 10 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 1 ms^{-1} decrease and 10% decrease, (c) 5 ms^{-1} increase and 50% increase, in mean annual wind velocity and mean annual rainfall, respectively.	334
Figure D.4: The risk of polishing, pitting, slurry and overall deterioration after 100 years of model time on a 10 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from modelled conservation strategies (b) a near windbreak, (c) a far windbreak and (d) two windbreaks and (e) 80% vegetation coverage.	335
Figure D.5: The deterioration risk and difference in deterioration risk for polishing pitting, slurry and overall deterioration after 100 years of model time on a 10 m long wall, under (a-c) a regime of low mean annual windspeed and rainfall, and (d-f) a regime of high windspeed and rainfall. Different conservation strategies were applied: (a, d) no conservation strategy (baseline); (b, e) addition of a windbreak and (c, f) 80% vegetation cover.....	336

Figure D.6: The risk of polishing, pitting and slurry after 100 years of model time on a 50 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 1 ms^{-1} decrease, (c) 2 ms^{-1} increase and (d) 5 ms^{-1} increase, in mean annual wind velocity. 337

Figure D.7: The risk of polishing, pitting and slurry after 100 years of model time on a 50 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 10% decrease, (c) 20% increase and (d) 50% increase in mean annual rainfall. 338

Figure D.8: The risk of polishing, pitting and slurry after 100 years of model time on a 50 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 1 ms^{-1} decrease and 10% decrease, (c) 5 ms^{-1} increase and 50% increase, in mean annual wind velocity and mean annual rainfall, respectively. 339

Figure D.9: The risk of polishing, pitting and slurry after 100 years of model time on a 50 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from modelled conservation strategies (b) a near windbreak, (c) a far windbreak and (d) two windbreaks and (e) 80% vegetation coverage. 340

List of Tables

Table 2.1: Types of earthen material (<i>Fodde, 2009; Velde, 2008; WHEAP, 2012</i>)	11
Table 2.2: Primary and secondary drivers of deterioration for earthen heritage and anthropogenic inheritance factors that influence deterioration. Compiled by author (<i>Cooke, 2008; Du et al., 2017; Rainer, 2008; Shao et al., 2013</i>).	19
Table 2.3: Conservation strategies applied to earthen heritage sites.....	25
Table 2.4: Methods used in rammed earth, earthen heritage studies according to their purpose of research. ‘^’ = Multiple methods used within the study; ‘*’=The study had multiple purposes. ‘HistM’= Historic Material taken directly from site for testing; ‘LabHistM’ = Samples prepared in the laboratory using historic material; ‘LabOth’ = Samples prepared in the laboratory using other material such as freshly sources soils; ‘TWall’ =Test walls located both in the field and laboratory; ‘Site’ = Measurements taken on site.....	32
Table 3.1: Examples of environmental and heritage science fields of research that have used a framework that combines field data and modelling.....	42
Table 4.1: Conditions used in the deterioration test	73
Table 4.2: The maximum depth and spatial extent of erosion after deterioration tests..	78
Table 5.1: Descriptions and the inferred causes of deterioration features at Suoyang.	100
Table 5.2: The types and severity of deterioration features present on the small test wall, large test walls and inner city walls	103
Table 5.3: Comparing the nature and distribution, frequency and magnitude and persistence of wind- and rain-driven deterioration features on earthen heritage	113
Table 5.4: Spatial controls on a) both wind- and rain-driven deterioration features, b) wind-driven deterioration features and c) rain-driven deterioration features	116
Table 7.1: Climate and conservation scenarios modelled using ViSTA-HD. A decrease in conditions in shown with a ‘-’, an increase is shown with a ‘+’	171
Table 8.1: Environmental, human and other drivers contributing to earthen heritage deterioration	203
Table 8.2: Trade-off factors for conservation strategies based on the ViSTA-HD model domain used in Chapter 7 (Paper 4).	216

Section 1

Research Context and Design



1 Introduction

1.1 Heritage, value and the environment

Heritage is a broad concept that encompasses all resources, both natural and cultural, which we “value for reason beyond mere utility” (English Heritage, 2008, pp 71). This means heritage can be both tangible and intangible (English Heritage, 2008; ICOMOS China, 2015), with tangible heritage taking many forms, from individual objects, to historic cities, to bio-diverse landscapes (Brooks, 2002). Worldwide, thousands of sites are seen as having heritage value by individuals, local communities, nations and international populations.

Heritage sites can help us understand the past; demonstrate evidence of human creativity in developing science and technology; have artistic creativity; provide educational benefits; and represent cultural diversity (ICOMOS China, 2015), as well as providing aesthetic stimulation and shaping the identities of individuals and communities (English Heritage, 2008). However, the value(s) given to specific heritage sites is dependent on many cultural, societal and geographic factors (De La Torre, 2013; Fredheim and Khalaf, 2016), with perceptions of value varying between countries, regions (Forster et al., 2018; Qian, 2007; Winter, 2014), and individuals (Harrison, 2013; Richards et al., 2018). To effectively conserve heritage, the value(s) of a heritage site need to be understood and all subsequent research should be undertaken within this values-based context (De La Torre, 2013). Working within such a context ensures that research is undertaken in a manner sensitive to the value of the site and provides outputs that are appropriate and usable for the given site (Avrami et al., 2000).

In addition, heritage research needs to view heritage sites within the context of their surrounding environment. Richards et al. (2019, p. 2) premised that “heritage cannot be considered and valued separately from the environment”. They argued that the environment is a co-creator of heritage, with the environment providing components for the construction of sites; modifying and being modified by the location of heritage sites; and adding value through processes such as creating patinas. With multiple environmental and anthropogenic processes such as climate and environmental change (Bosher et al., 2019; Brimblecombe et al., 2010), rapid urbanisation (Bosher et al., 2019; Cui et al., 2011), pollution (Thornbush and Viles, 2005) and conflicts around the world (Najimi, 2011) causing deterioration to heritage sites, understanding how heritage sites interact within the wider environmental system is vital for holistically assessing and minimising the risk to them from complex threats.

To conserve heritage sites, strategies can range from deliberately doing nothing, through monitoring and minor repair work, to reconstruction (ICOMOS China, 2015). For strategies that aim to minimise the loss of heritage value by reducing the rate of deterioration at heritage sites, these generally aim to either strengthen the historic material or attenuate adverse environmental conditions (Oliver, 2008). Past conservation strategies have predominately been applied to the historic material, with many reducing deterioration rates in the first couple of years after application (L. Li et al., 2011; Selwitz, 1995; Zhang et al., 2017a). However, many have had an impact only in the short term, while some of these interventions have increased the rates of deterioration in the longer term (Lister and Lister, 1987; Matero, 1999). Increasing our understanding of the interactions between the environment and heritage sites should

enable the development of successful conservation strategies that minimise deterioration over timescales of decades to centuries.

1.2 Earthen heritage

Earthen heritage is a broad category of heritage that includes archaeological sites, buildings and burial mounds made from materials such as rammed earth, adobe and wattle and daub (WHEAP, 2012). Earthen sites are found on every continent except Antarctica with numerous sites found along the ancient Silk Road in central to eastern Asia (L. Li et al., 2011; WHEAP, 2012). Earthen sites along the Silk Road have important historic, scientific and cultural values (Richards et al., 2018): they provide evidence for the exchange in goods, knowledge (cultural and scientific) and religion between western and eastern civilisations (UNESCO, 2014; WHEAP, 2012). Many of these sites are exposed to harsh environmental conditions and given the low durability of earthen materials when exposed to environmental agents such as wind and rain (Beckett et al., 2020), many sites experience high rates of deterioration (Shao et al., 2013; X. Wang et al., 2010; Zhao et al., 2016). Consequently, there is an urgent need to understand the current drivers of deterioration and investigate potential long-term conservation strategies for these earthen heritage sites.

The emergence of Heritage Science over the last decade has highlighted the crucial role scientific research plays in providing physically based, analytical approaches for developing and monitoring conservation solutions (Strlič, 2018; Williams, 2009). Research on earthen heritage can, in particular, draw on understandings from geomorphology. Geomorphology studies the interaction between environmental

processes and the earth's surface, investigating how complex processes cause landscapes to be shaped (Goudie and Viles, 2010). Consequently, many geomorphological concepts (e.g. spatial and temporal scale, magnitude and frequency, erodibility and erosivity) and methods (e.g. field-based research and modelling) are highly relevant for understanding interactions between the environment and earthen heritage.

To undertake research on earthen sites that have heritage status, multi-national perspectives enable views from multiple stakeholders to be considered – even if they are contradictory (Dutta and Husain, 2009; Ferretti et al., 2014; Su and Wall, 2012). International collaborations ensure that expertise is not limited to one institution or one country, but instead a global pool of resources can be used to tackle some of the most urgent questions currently facing heritage and heritage conservation. For earthen sites on the Chinese section of the ancient Silk Road, the establishment of international collaborations (e.g. between the Dunhuang Academy, China and the Getty Conservation Institute, USA) marks a new approach to heritage conservation where developing strong ties between institutions is at the core of the strategy (Zhu, 2012).

As well as being international, collaborations also need to be trans-disciplinary (Bond and Worthing, 2016; Brabec and Chilton, 2015). They need to go beyond academic institutions and include people in charge of authorising and implementing conservation strategies at specific heritage sites (such as heritage practitioners, site managers and conservators), thus enabling a mutual transfer of knowledge between research and the site-based implementation of strategies (Kennedy, 2015).

This thesis draws on approaches used in geomorphology and heritage science to investigate the environmental drivers of, and potential conservation strategies for, earthen heritage. Due to the complexity of interactions between environmental and deterioration processes, this research focuses on the site of Suoyang Ancient City, Gansu Province, northwest China, but is applicable to other earthen sites located in dryland areas.

The research has been undertaken within the EPSRC SEAHA (Science and Engineering in Arts, Heritage and Archaeology) Centre for Doctoral Training and in collaboration with the Dunhuang Academy, China, and the Getty Conservation Institute, USA. Both organisations have been instrumental in providing an international perspective on the project and ensuring that findings have the potential to inform the conservation management strategies of earthen heritage sites.

1.3 Overview of thesis

This thesis is article-based; it is comprised of academic papers that have been submitted for publication in peer reviewed journals. It presents four papers accompanied by introductory sections outlining the research context and design; linking sections between papers; and a final discussion and conclusion. In accordance with the submission guidelines, the four papers presented in the thesis are in their submitted/published format. The work within this thesis is largely my own and a statement of author contributions to each paper can be found in Appendix A.

This thesis is comprised of four sections: (1) research context and design, (2) environmental drivers of earthen heritage deterioration, (3) the future of earthen heritage deterioration and (4) conclusions (Figure 1.1).

In **Section 1**, a review of earthen heritage deterioration and conservation is provided along with the aim and objectives of this thesis. A research framework and overview of methods is also presented.

Section 2 focuses on interactions between earthen heritage and its surrounding environment. **Paper 1** uses a controlled field experiment to examine how environmental drivers of deterioration (wind and rain) impact earthen heritage. These findings are developed in **Paper 2** which investigates the relative importance of wind and rain in driving earthen deterioration.

Section 3 evaluates the risk posed by environmental drivers of deterioration to earthen heritage under future conservation and climate scenarios. **Paper 3** presents a new enviro-heritage model, which spatially resolves the risk of deterioration across a wall face. **Paper 4** uses this model to assess how changes in climate may affect the risk of deterioration at earthen heritage sites and to what extent this risk can be minimised by nature-based conservation strategies.

Section 4 discusses four themes that emerge from the four papers to consider the implications of the findings within a wider research context. The objectives of the paper are addressed in the final conclusions and potential avenues for further research are suggested.

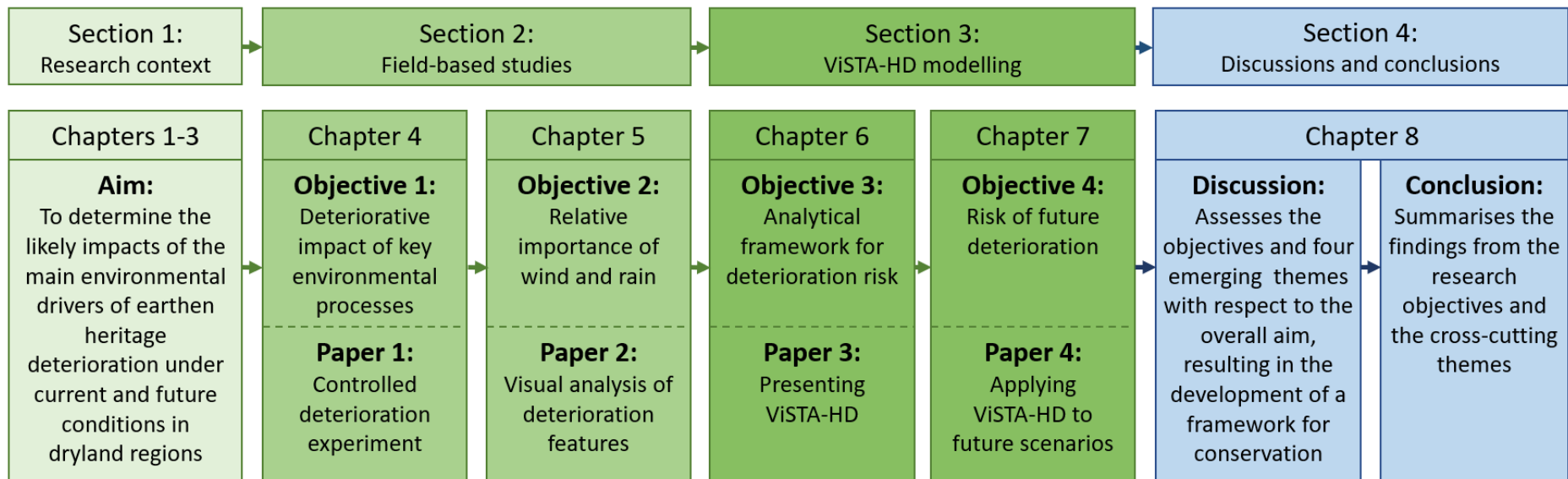


Figure 1.1: Thesis structure comprised of four overarching sections and eight chapters

2 Earthen heritage research: Past, present, future

2.1 Earthen Heritage

Earthen heritage, considered to be any form of heritage composed of earthen material such as soil or loess (Velde, 2008; WHEAP, 2012), is one of the oldest and most universal forms of heritage with sites dating back to Neolithic times and is found on every continent except Antarctica (Balderrama, 2001; Houben et al., 2004; Twiss, 2007).

Earthen heritage provides humanity with a rich and multifaceted understanding of the past (UNESCO, 2014), encompassing a wide and highly varied array of cultural heritage sites from buildings to burial mounds (Daniel, 1970; Dillehay, 1990; Domínguez Martínez et al., 2014; Lourenço et al., 2019); and from temples to cities (Barnas and Kania, 2019; Z. Li et al., 2011; Shao et al., 2013).

As introduced in Section 1.2, earthen sites provide us with historic, cultural and scientific value (Richards et al., 2018; UNESCO, 2014) and continue to play a vital role in contemporary 'living' heritage (Fodde, 2009; Luo et al., 2019). For example, the range of earthen building materials used at the ancient City of Nevaket, Kyrgyzstan, demonstrate the blend of Indian, Turkic, Sogdian and Chinese influences in the region, while the presence of a Zoroastrian burial ground, three Buddhist temples, and Nestorian inscriptions at the site provide evidence for the spread of multiple religions in the area (UNESCO, 2014). In addition, numerous earthen sites, such as the Medina of Fez and Historic City of Meknes in Morocco, are still inhabited, influencing the local culture as well as providing homes, businesses and local services to the community (WHEAP, 2012). The importance of earthen heritage as part of our collective cultural heritage

(Houben et al., 2004) is reflected in the World Heritage List where earthen sites comprise approximately 10% of listings (Figure 2.1; WHEAP, 2012).

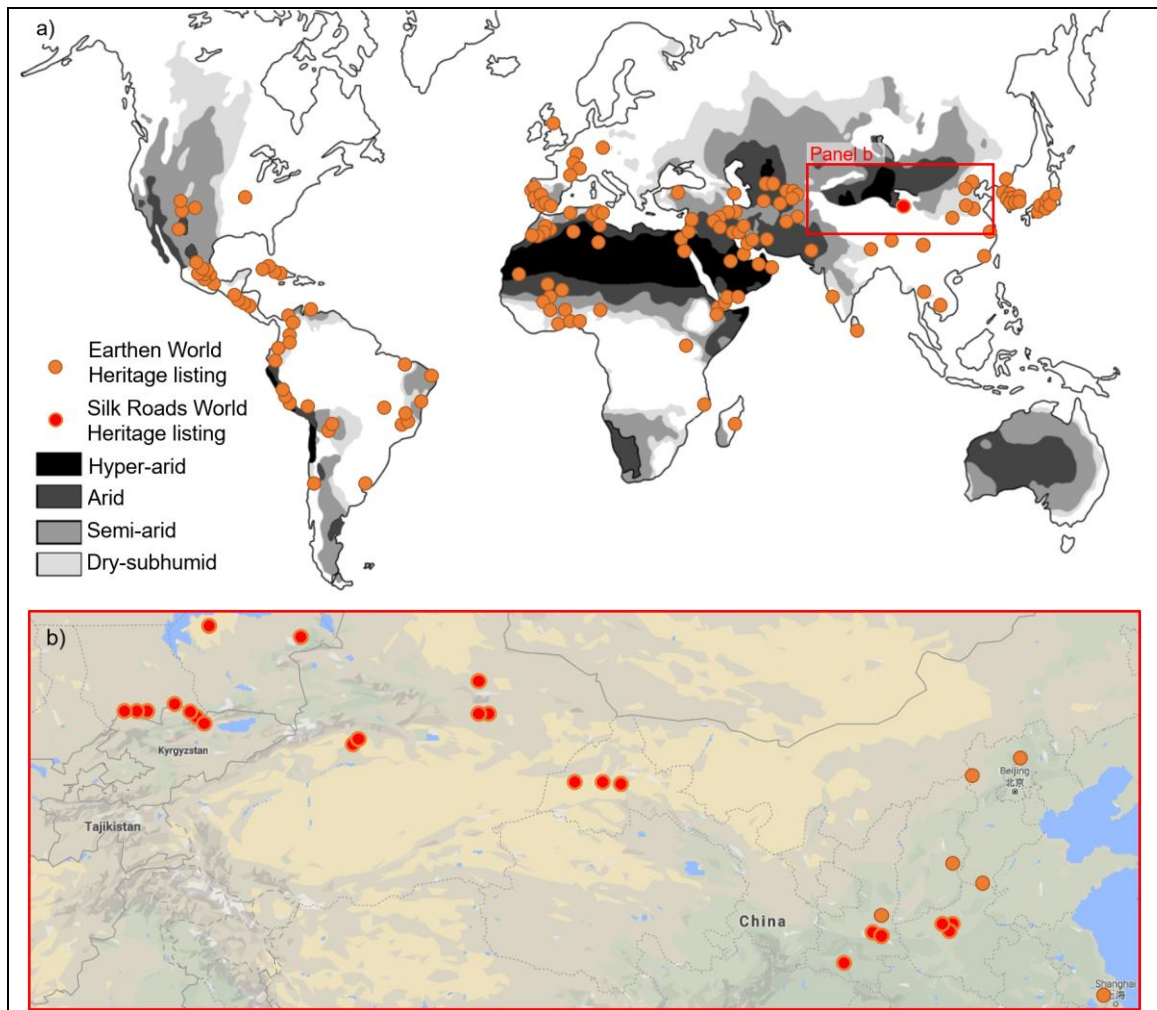


Figure 2.1: The distribution of earthen world heritage listings a) in dryland regions. As one world heritage listing can be comprised of many heritage sites, b) shows the distribution of earthen sites that comprise the Silk Roads world heritage listing (represented by only one dot in panel a). Maps were created by the author, adapting figures from *Thomas (2011)* and *WHEAP (2012)*.

Materials used to construct any given site are dependent on local materials, climate and building practices (Correia et al., 2015). For earthen heritage, the most common forms of material are: rammed earth, adobe, wattle and daub and cob (see Table 2.1 for definitions and examples). While the strength of a material is a key factor in determining structural stability, the failure of earthen structures has predominantly been linked to the material's low durability to resist environmental, seismic or anthropogenic damage, rather than its strength (Beckett et al., 2020; Morel et al., 2012). Consequently, earthen

heritage sites are highly susceptible to deterioration, especially if they are not continually maintained (Rainer, 2008).

Table 2.1: Types of earthen material (Fodde, 2009; Velde, 2008; WHEAP, 2012)

Material type	Construction technique	Examples of sites formed predominately from the given material type
Rammed earth	A layer of raw earth is placed in a mould and rammed down with a tamper. Subsequent layers are added until the desired height is reached.	Suoyang Ancient City, China Fujian Tulou, China Potala Palace, Tibet, China The Great Wall, China Serón de Nágima castle, Spain Alhambra Palace, Spain Historic Centre of Évora, Portugal Historic City of Meknes, Morocco
Adobe	Earth is typically mixed with water and additional materials such as straw and formed into brick-sized moulds and left to dry.	Cahuachi, Peru Fort Union, USA Bam Citadel, Iran Hatra, Iraq Citadel of at-Turaif, Saudi, Arabia Old Towns of Djenné, Mali Tomb of Askia, Mali Ancient Thebes and its Necropolis, Egypt Ksar of Ait-Ben-Haddou, Morocco
Wattle and daub	Earth is mixed with water and additional materials such as straw and dung and applied to a woven lattice usually made out of wooden strips	Çatalhöyük, Turkey Ashanti houses, Ghana Tombs of Buganda Kings, Uganda Talbot House, UK Provins, France Himeji-Jo, Japan Jongmyo Shrine, Republic of Korea
Cob	Clay-based soil is typically mixed with water sand and straw and laid into a foundation before drying.	Royal Palaces of Abomey, Benin Osun-Osogbo Sacred Grove, Nigeria Old City of Sana'a, Yemen Itchan Kala, Uzbekistan Historic Centre of Morelia, Mexico

2.1.1 Earthen heritage research

Research into earthen heritage has grown exponentially since the 1970s, aided by a series of twelve international Terra conferences on Earthen Architectural Heritage (Teutonico, 2008). Over the last 50 years, these conferences have been noted by

researchers, such as Avrami and Guillaud (2008), as being key for the development of earthen heritage research by providing a setting for exchanging ideas and fostering international collaborations. They have also shaped the research and policy agenda with conferences producing recommendations aimed at influencing decision-makers, research agendas and improving knowledge transfer and engagement (World Congress TERRA, 2016).

Earthen heritage research is now undertaken by researchers and practitioners from a wide range of disciplines. For example, engineers and material scientists have studied the structural properties of earthen materials; architects have assessed how sites were designed; conservators have implemented strategies to minimise the loss of a site's value; and geographers have investigated the impact of environmental processes on earthen sites (Avrami and Guillaud, 2008; Ford et al., 1997; Lombillo et al., 2014; Oliver, 1983).

With this broad research base, interdisciplinary approaches and methodologies are now commonly used in earthen heritage research. For example, interviews and questionnaires have been used to define criteria for earthen heritage conservation (Rosado Correia and Walliman, 2014), while laboratory tests associated with material sciences have determined how conservation strategies alter material properties (Q.-B. Bui et al., 2014).

These interdisciplinary approaches have resulted in significant advances in our understandings of:

- the value of earthen heritage, with earthen heritage being viewed as historically, scientifically and culturally valuable (Avrami and Guillaud, 2008; Richards et al., 2018; UNESCO, 2014).
- the complexity of how the properties of earthen materials vary with environmental conditions, for example water content directly affecting material properties such as shear strength and the modulus of elasticity (Bui et al., 2011, 2009; Bui and Morel, 2009; Guillaud, 2008; Velde, 2008; Wu et al., 2012).
- minimising the vulnerability of earthen heritage to seismic events (i.e. earthquakes) using structural reinforcements (e.g. Bui et al., 2019, 2020; T.-T. Bui et al., 2014; Cuadra et al., 2008; Kim and Park, 2014; Newmann, 2010; Ravankhah et al., 2017; Webster, 2008).
- material-based conservation of earthen heritage, with a range of strategies such as the application of consolidants, wall capping and drainage systems reducing deterioration rates in the short term (Correia and Guerrero, 2018; Z. Li et al., 2011; Oliver, 2008; Rosado Correia and Walliman, 2014; Zhang et al., 2017a).

However, despite these huge advances, Rainer (2008, pp 52-53) noted:

“Relatively little has been published that specifically addresses the weathering processes of earthen buildings and materials. Literature related to stone is much more common in this area. Given the vulnerability of earthen materials to erosion and weathering, further research should be carried out, with an eye toward developing preventive conservation measures.”

In the decade since Rainer noted this lack of research, there has been limited progress. A literature review by Beckett et al. (2020) highlighted that only ~3% of earthen literature

was focused on the durability of earthen materials to environmentally-driven weathering processes. However, even this paper, which aimed to promote the need for a greater focus on environmental agents of deterioration, only discussed deterioration caused by water without mentioning the role of other agents such as wind. As such, improving our understanding of how environmental processes interact with, and potentially deteriorate, the historic material is vital for developing effective conservation strategies for earthen heritage sites (Figure 2.2).

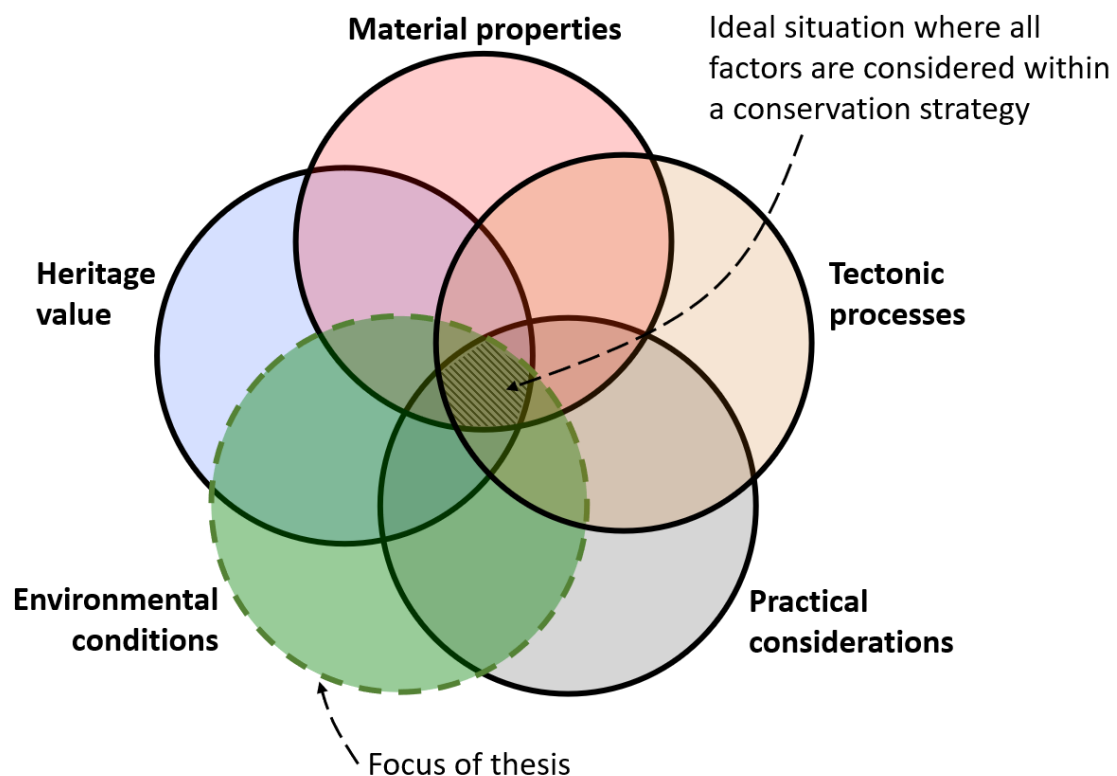


Figure 2.2: Key factors for developing effective conservation strategies.

A limited number of field-based studies, such as those undertaken at Jiaohe Ancient City (Z. Li et al., 2011; Shao et al., 2013), have described the presence of deterioration features at earthen sites but have not linked these features to specific causal mechanisms. Du et al. (2017) developed a conceptual model for earthen deterioration. Whilst Du et al.'s model links some environmental processes with deterioration, such as linking precipitation with sapping (under cutting), it is not comprehensive: it does not

link precipitation with other deterioration features such as gullying or collapses and it does not consider any interactions or feedbacks between environmental processes. Recently, Cui et al. (2019) investigated the processes causing the occurrence of scaling off (where a crusted layer is detached from the parent material) on earthen heritage. This study used data from 18 earthen sites in northwest China and suggested a highly detailed mechanism for the development of this feature. However, as this study only investigated one formation of scaling off, further work is needed to understand: (i) how other common deterioration features such as pitting and slurry are caused by environmental processes; and (ii) how conservation strategies could try to minimise the deteriorative interactions between environmental processes and earthen heritage.

As each type of earthen material has its own complex set of material properties and interactions with environmental processes, it is beyond the scope of this thesis to consider all types of earthen material in all environments. Consequently, this thesis will focus on rammed earth as many sites constructed of rammed earth are experiencing high rates of deterioration (T.-T. Bui et al., 2014; Cui et al., 2019a; Du et al., 2017; Z. Li et al., 2011; Luo et al., 2019; X. D. Wang et al., 2010). Rammed earth has received a smaller proportion of research focus compared to other earthen materials such as adobe (Barnard et al., 2016; Elert et al., 2015; Guerrero, 2002; Matero, 2015). Moreover, rammed earth sites comprise one in five earthen world heritage sites and form a notable proportion of national and regionally important sites (UNESCO, 2014; WHEAP, 2012).

2.2 Rammed Earth

2.2.1 *Construction and material properties*

Rammed earth structures are constructed by laying temporary frameworks in the shape of the desired wall. A layer of damp earth is poured into the mould (~30cm in depth, although this can significantly vary) and compressed using high energy impacts (Jaquin et al., 2008; Velde, 2008). This process is repeated until the wall has reached its required height. Rammed earth structures have a distinctive horizontal stripe pattern due to the upper part of each rammed earth layer being more densely packed (Historic England, 2015).

Compaction causes water to be expelled from the material, particles approach each other by force rather than mutual attraction between grains, forming an isotropic, partially consolidated material (Bui and Morel, 2009; Velde, 2008). Rammed earth tends to be formed of 50- 65% sand, 25- 35% silt and 5 – 10% clay (Q.-B. Bui et al., 2014; T.-T. Bui et al., 2014; Miccoli et al., 2014), although this can vary.

Clays found in earthen materials include kaolinite, illite, chlorite and smectite, which has a notably large shrink/swell capacity (Velde, 2008). The quantity of clay influences the material's erodibility as strong van der Waal forces between the small clay particles requiring more energy to be eroded than larger particles such as silt and sand. As the proportion of clay in rammed earth is lower than in other earthen materials, rammed earth has comparatively greater proportion of particles susceptible to weathering (Shao et al., 2013).

2.2.2 Rammed earth sites

Rammed earth has commonly been used as a construction material in semi-arid to arid environments due to the widespread availability of earthen materials along with the lack of other common building materials, such as stone and timber (Figure 2.1; Li, Shao, et al., 2011; WHEAP, 2012). In these dryland regions, rammed earth has been used to form a variety of structures including ancient cities, palaces, forts, signal towers and boundary walls that are now considered as cultural heritage sites (Cui et al., 2012; Pu et al., 2016a; X. Wang et al., 2010).

China's ancient civilisations were rich in cultural heritage resources, and thousands of artefacts, and hundreds of historic towns and sites, have been recognised as nationally and provincially important (Zhu, 2012). Earthen heritage forms an important part of China's extensive cultural heritage, with the Chinese earthen site of Dadiwan dating back to the Neolithic period (Li, 1990; WHEAP, 2012).

Earthen sites are particularly important along the semi-arid to arid region of the Silk road, stretching west from Xi'an (Figure 2.1b; Li, Shao, et al., 2011). Here, earthen sites include sections of the Great Wall of China (Pu et al., 2016a), ancient cities such as Suoyang and Jiaohe (Z. Li et al., 2011; Shao et al., 2013), defensive structures such as Yumen fort and watch tower (X. Wang et al., 2010), and religious building such as monasteries and temples (L. Li et al., 2011). Of the 33 sites which form the Silk Roads' World heritage listing, three quarters have notable or significant earthen architectural elements – providing invaluable historic evidence for the transfer of goods, knowledge, culture and religion between ancient Eastern and Western civilisations (UNESCO, 2014).

However, despite the importance of earthen heritage in this region, many sites such as Jiaohe, Yumen and Suoyang are experiencing high rates of deterioration (L. Li et al., 2011; Pu et al., 2016a; Shao et al., 2013; X. Wang et al., 2010; X. D. Wang et al., 2010). For example, the ancient city of Jiaohe, located in the northwest Xinjiang Region of China, has experienced extensive deterioration with widespread cracking, pitting, slurring and in some instances wall collapses across multiple wall faces (Z. Li et al., 2011; Shao et al., 2013).

Please note, hereafter, earthen heritage refers to sites built using the rammed earth method unless otherwise stated.

2.3 Deterioration processes

Earthen heritage deterioration is influenced both by the environmental conditions (Bui et al., 2009; Mao et al., 2015; Pu et al., 2016a) and the material characteristics of a site (Du et al., 2017). Previous earthen heritage deterioration research has tended to focus on understanding how specific material characteristics, such as shear strength, grain size and salt content, influence the material's susceptibility to deterioration (Bui et al., 2011; Q.-B. Bui et al., 2014; Gomes et al., 2019, 2016; Mao et al., 2008; Shen et al., 2017; Wu et al., 2012). However, the durability of earthen materials to environmental processes has been argued to be the major control on deterioration (Beckett et al., 2020; Morel et al., 2012). Therefore, further understanding of how environmental conditions drive deterioration processes is vital (Rainer, 2008).

In geomorphology, the concept of drivers has been used to explain the factors which cause processes to occur in a specific manner (Cooke et al., 1993; Lancaster, 1995). By

applying this approach to earthen heritage, environmental conditions including wind and sediment transport (Luo et al., 2019; Mao et al., 2015, 2008), precipitation (Huang and Peng, 2015; Luo et al., 2019), temperature (Cui et al., 2019b; Zhao et al., 2012) and solar insolation (Sun et al., 2011) can be viewed as primary drivers of earthen deterioration (Figure 2.3; Table 2.2). Gravity also plays an important role in driving mass-movements at earthen heritage sites. However, due to the exposure of many earthen heritage sites in dryland regions to strong sediment laden winds and heavy rain, this research focuses on the impact of environmental drivers.

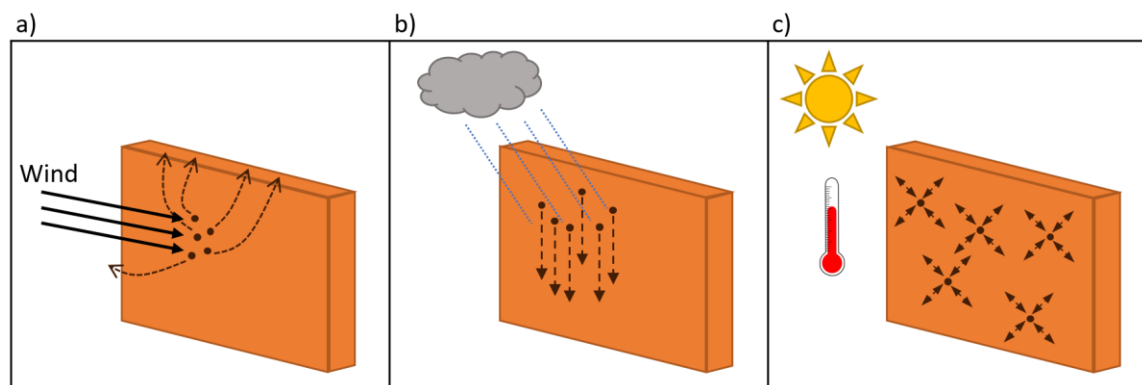


Figure 2.3: Schematics of earthen heritage deterioration driven by (a) wind, (b) rain and (c) solar insolation and temperature. The dotted arrows indicate the movement of particles.

Table 2.2: Primary and secondary drivers of deterioration for earthen heritage and anthropogenic inheritance factors that influence deterioration. Compiled by author (Cooke, 2008; Du et al., 2017; Rainer, 2008; Shao et al., 2013).

Primary	Secondary	Anthropogenic Inheritance
Wind	Salt content	Choice of building materials and building technique
Sediment transportation	Vegetation coverage	Modifications and repairs
Precipitation	Changes in relative humidity	Human activity (e.g. warfare, farming practices)
Temperature	Changes in soil moisture	Neglect
Solar insolation	Clay content	Conservation strategies
	Organic content	

When these primary drivers interact with earthen heritage, they also interact with secondary drivers that can cause deterioration (Table 2.2). For example, rain is a primary driver of deterioration as it can directly causing deterioration processes such as rain drop erosion, slumps and slides (Bruno et al., 1968). However, it can also drive secondary deterioration processes as it can cause salts in the material to crystallise, hydrate and deliquesce resulting in earthen heritage being subjected to salt weathering (Shen et al., 2017; Y. Zhang et al., 2016).

Deterioration will also be affected by the inheritance of anthropogenic processes that occurred during the site's occupation (e.g. the location of holes for construction timbers, availability of building material, repairs features) and conservation efforts since its abandonment. Whilst we would ideally understand all primary and secondary drivers of deterioration and the inherited anthropogenic impacts, given the complexity of interactions which occur within earthen material and between earthen material and the surrounding environment, this is not currently feasible. I will focus on the interactions between the primary drivers of deterioration and earthen heritage as, if the primary drivers of deterioration are able to be minimised, it is likely to also minimise the related secondary drivers.

Previous deterioration studies at earthen sites located in China have noted the deteriorative impact of multiple environmental conditions including wind, sediment transport, rain, snow, freezing temperatures and solar insolation (Jo et al., 2018; L. Li et al., 2011; Shao et al., 2013; Sun et al., 2011; X. D. Wang et al., 2010; Zhang et al., 2018). Given many earthen heritage sites are located in remote, transport-limited dryland environments, which are exposed to harsh wind regimes with sporadic, heavy rainfall

events - wind, sediment transport and rain have been highlighted as dominant drivers of deterioration (Du et al., 2017; Shao et al., 2013). Pu et al. (2016) and Cui et al. (2019) examined the effect of snowfall and freezing temperatures on earthen heritage. They found that materials exposed to these conditions suffered reductions in tensile and compressive strength and were more susceptible to wind erosion.

In this thesis, I focus on the role of rain and wind as drivers of deterioration. This decision was informed by the expert opinions of researchers at the Dunhuang Academy coupled with results from a preliminary site visit where deterioration features associated with wind and rain were extensively seen across the site. However, given the occurrence of winter snowfall in cold desert environments future research should further investigate the role of snowfall and freezing temperatures to increasing rates of deterioration.

In this thesis I will define deterioration processes and features using the terminology used by researchers who undertake research at earthen heritage sites in north west China (e.g. Shao et al., 2013; Cui et al., 2019). This terminology can sometimes differ from standard Western nomenclature. However, it enabled continuation of terminology used by the Dunhuang Academy, aiding communication and understanding between researchers. A glossary and atlas of deterioration features referred to in this research are provided in Appendix E.

2.3.1 Rain

Rain weakens the cemented material between soil particles, allowing particles to be entrained and transported down the wall face due to gravity (Shao et al., 2013). It has been noted as causing high rates of deterioration at earthen heritage sites, with single

rain events having the potential to result in visible material loss (Beckett et al., 2020; Bui et al., 2009; Crosby, 1983; Fodde and Khan, 2013; Rainer, 2008). Results can include the formation of slurry down the wall face as well as gullies, slips and collapses (Du et al., 2017). Material deposited down the wall face can cause the formation of a harder crust (Cui et al., 2019a).

2.3.2 Wind and sediment transport

Wind can abrade earthen heritage by removing loose or weakened material from the site (Shao et al., 2013). When sediment is entrained within the wind, the erosional power of the wind exponentially increases (Mao et al., 2015). The impact of the kinetic energy of the sand on the earthen material can cause particles to be loosened, making them susceptible to being entrained and removed by the wind (Mao et al., 2015). This can result in the formation of features such as sand polishing and pitting. In addition, the high erosivity of sediment laden wind can result in the breaking surface crusts exposing weaker material to erosion (Cui et al., 2019a; Zhang et al., 2009). Laboratory experiments have identified 12 m s^{-1} as a threshold for deterioration caused by sediment laden wind to occur (X. D. Wang et al., 2010) but little work has been undertaken to understand if this is reflective of deterioration in the field.

2.3.3 Variations and interactions between drivers of deterioration

Whilst research has been undertaken that assesses the impact of individual drivers on earthen heritage deterioration, limited research has focused on the interaction between, and impact of, multiple drivers of deterioration, especially in the field (Cui et al., 2019a; Du et al., 2017; Shao et al., 2013). Cui et al. (2019) found that scaling off is a function of fluctuations in water, wind, salt and temperature, and so only when

considering the interactions between these functions can the process of scaling off be understood. This suggests that research looking at the impact of single processes may not capture the complexity of deterioration processes. Consequently, there is a need to understand how multiple processes interact and how these impacts on the deterioration of earthen heritage.

In addition, there has been only limited research assessing how the frequency or magnitude of environmental-drivers of deterioration impact earthen heritage. For example, some drivers, such as rain, occur infrequently but cause high rates of deterioration (Shao et al., 2013) while other drivers, such as wind, occur far more frequently but at lower rates of deterioration (Mao et al., 2015). Understanding how the frequency and magnitude of such events affects the rate and type of deterioration is vital for implementing successful conservation strategies.

Moreover, the environment in which earthen heritage is situated has not remained constant over time. Climatic and environmental changes mean that drivers of deterioration are highly likely to have also varied over the time period since many sites were constructed (Brimblecombe et al., 2011, 2010). This is especially important for earthen heritage in dryland regions as these areas can be sensitive to climatic and environmental changes (Huang et al., 2017, 2016). Consequently, processes occurring at earthen heritage should be considered in the context of past conditions and how this may have affected present day processes.

Therefore, to minimise deterioration at earthen heritage sites, not only is a holistic understanding of the drivers of deterioration required, but conservation strategies which mitigate against the (potentially changing) drivers of deterioration are needed.

2.4 Conservation approaches

Heritage conservation is the process that tries to manage change at a heritage site through the implementation of maintenance, technical interventions and management strategies (English Heritage, 2008; ICOMOS China, 2015). As such, conservation should aim to:

“preserve and protect the authenticity and integrity of the site, its historic information and values, using both technical and management measures”

(ICOMOS China, 2015, pp 61)

For earthen heritage sites, many conservation strategies have been trialled (Table 2.3). Strategies have predominantly tried to decrease the erodibility of the historic material (e.g. surface treatments, wall capping, structural reinforcements, drainage). Whilst these methods are generally effective in the short term at minimising rates of deterioration, they can cause irreversible change to the historic material (H. Zhang et al., 2016), require ongoing maintenance (Chiari, 1990) and can also unintentionally alter other processes such as moisture regimes and salt mobilisation which, in turn, can increase rates of deterioration (Correia et al., 2015; Warren, 1999).

Table 2.3: Conservation strategies applied to earthen heritage sites

Treatment	Conservation aim	Potential negative consequences	Examples: Study	Material	Location
Historical: dung, urine, blood and slaked limes	Strengthen earthen material	Change moisture and salt regimes in the historic material	Lunt (1980) Orazi (2000) Kraus et al. (2013)	Historic treatment Adobe Historic treatment	N/A Khor Rori, Oman N/A
Surface stabilisers	Modify the physical or chemical characteristics of the soil	Can cause irreversible changes to the historic material composition	Elert et al. (2008) Elert et al. (2015)	Rammed earth Adobe	Alhambra, Spain N/A
Surface additives	Improve soil properties without interfering with chemical reactions	Change moisture and salt regimes in the historic material	H. Zhang et al. (2016)	Adobe	Da Bao'en Temple, China
Surface consolidants	Join earthen particles together	Change the physical structure of the historic material	Chiari (1990) Koob et al. (1990) Li (1990) Selwitz et al. (1990) Selwitz (1995) Mao et al. (2008) X. Wang et al. (2010) Z. Li et al. (2011) Zhao et al. (2016)	Adobe Adobe Not Specified Adobe Adobe Rammed earth Rammed earth Rammed earth Rammed earth	Tell 'Umar, Iraq Gordion, Turkey Dadiwan, China Fort Selden, USA Fort Selden, USA Gaochang Ruins, China Hecang Fortress, China Jiaohe City, China Gaochang Ruins, China
Wall capping	Act as a sacrificial layer to reduce the vertical erosion and direct water away from the wall face	Can trap moisture in the wall and cause salt to be deposited, accelerating erosion at the interface and walls upper sections. Can also alter the flow of water around the wall causing undercutting	Torraca et al. (1972) Chiari (1990) Hoyle (1990) Taylor (1990) Selwitz (1995) Alva and Chiari (1995) Guerrero (2002)	Adobe Adobe Adobe Adobe Adobe Adobe Adobe	Al-Mada'in, Iraq Tell 'Umar, Iraq Chan Chan, Peru Fort Selden, USA Fort Selden, USA Mediterranean N/A
Structural reinforcement	Strengthen historic structure	Can cause a loss of historic material and can change the aesthetic of the site	X. Wang et al. (2010) Z. Li et al. (2011) Angulo-Ibáñez (2017)	Rammed earth Rammed earth Rammed earth	Yumen Pass, China Jiaohe City, China N/A

Drainage	Promotes the movement of water away from an earthen site	Can alter the shape and form of the site. Installation can cause shrinkage and cracking to occur	Lister and Lister (1987) Caperton (1990) Caperton (1993) Hughes (1998) Chaudhry and Sikka (2009) Fodde and Khan (2013)	Adobe Adobe Adobe Adobe Adobe Adobe	Aztec Great Kiva, USA Fort Selden, USA Fort Selden, USA Moenjodaro, Pakistan Western Himalayas Moenjodaro, Pakistan
Shelters	Protect sites from extreme climates	Can change the temperature and humidity, alter flow of water round site and increase wind speeds	Agnew et al. (1996) Aslan (1997) Matero (1999) Mazar (1999) Matero and Moss (2004)	Adobe Review paper Adobe Adobe Adobe	Fort Selden N/A Casa Grande Ruins, USA Tell Qasile, Israel Çatalhöyük, Turkey
Burial	Recreates the environment which has enabled a site's preservation	Limits access for researchers and the public	Chiari et al. (2000) Barnard et al. (2016)	Adobe Adobe	Cardal, Peru Karanis, Egypt

On the other hand, the deterioration of earthen heritage can also be reduced by minimising the erosivity of the environmental conditions before they interact with the site by, for example, constructing shelters or re-burying sites (Oliver, 2008). The concept of reburial as a viable strategy has gained momentum over the last decade as it recreates the environment that has enabled a site's preservation (Barnard et al., 2016; Chiari et al., 2000). However, burial also limits access for researchers and the public. Shelters mean the site can remain accessible whilst protecting the site from extreme conditions (Matero and Moss, 2004; Mazar, 1999). However, given the complexity of interactions between heritage sites and their surrounding environment, shelters can change the micro-climate of the site as well as altering the flow of water around the site, which in some cases increases deterioration rates (Agnew et al., 1996; Matero, 1999).

2.4.1 Conservation practices in China

Whilst conservation strategies should minimise deterioration rates, many other factors need consideration, including:

- how a conservation strategy affects a site's authenticity, integrity and value; and
- practical implications of a strategy such as installation and maintenance costs

(English Heritage, 2008; ICOMOS China, 2015).

Given that ideas of what constitutes authenticity, integrity and value are highly subjective, varying between traditionally Western and Eastern conservation perspectives and person to person (Jones, 2009; Pendlebury et al., 2009; Winter, 2014; Zhu, 2015), implementing a conservation strategy that satisfies all stakeholders can be highly challenging.

In China, contemporary conservation is seen as having developed in the early 1900's through the work of Zhu Qiqian (Zhu, 2012). Since then, conservation has undergone four main periods: (i) the 'fundamental period' (1929 – 49) which included the investigation of sites in need of urgent conservation as well as passing local law on conservation; (ii) the 'practical period' (1950 – 78) in which central government issued national laws which ordered the listing of heritage items; (iii) the Cultural Revolution (1966 – 78) where traditional culture was denounced and many cultural relics and sites were destroyed; and (iv) the 'Open Communication Period' (from 1979), where international collaborations for conservation have been established but also marks a period with challenges such as balancing rapid urbanisation with conservation needs (Jun, 2014; Zhou, 2008; Zhu, 2012).

In 1982, the first Law for the Protection of Cultural Relics was passed and was subjected to extensive amendments in 2002. The original and revised versions of the law aimed to strengthen state protection of cultural heritage sites while also balancing the needs for exploitation as well as preservation of cultural heritage. The developments in China's management system are reported in the Blue Book of Cultural Heritage which outlines future tasks for improving the management of heritage conservation.

In addition, the *Principles for the Conservation of Heritage Sites in China*, (hereafter, the China Principles) were developed to help govern conservation practice. The China Principles were originally published by ICOMOS China in 2000, through collaboration between China, America and Australia (Qian, 2007) and has since been published bilingually in 2015 (ICOMOS China, 2015). Both the Dunhuang Academy and the Getty Conservation Institute, who have provided support for this research in this thesis,

worked to trial the application of the principles at the Mogao Grottoes, Dunhuang, China, in the late 1990s. Conservation at this site has continued to follow the China Principles and these Principles are also used to inform the conservation of other sites in which the Dunhuang Academy are involved.

The China Principles are predominantly aligned with Western conservation concepts, but conservation practice within China has varied substantially. This has been argued to be caused, at least in part, by authenticity being viewed as an imported western concept (Xu et al., 2014). Authenticity can be translated into Mandarin either as: *yuanzhenxing* (原真性), which means ‘the original true state’ and refers to the original state of the site, thus supporting site reconstructions; or as *zhenshixing* (真实性), which means ‘true state’ and refers to the current condition of the site (Han et al., 2016). Consequently, negotiating differences between Chinese policy and practice as well as other international perspectives can be complex, but is vital when, for example, applying conservation to Chinese World Heritage Sites (as well as others globally) and working within international collaborations.

2.5 Cultural similarities in approaches to earthen heritage conservation

In China, earthen heritage conservation research has predominantly been focused on the application of consolidants and structural reinforcements (see Table 2.3). However, as these strategies change the physical structure of the historic material and can be time intensive to implement and maintain, alternative strategies may be preferable.

Richards et al. (2018) ran an innovative bi-lingual workshop to investigate how heritage experts based in China and the UK would aim to conserve Chinese earthen heritage, with

specific reference to the site of Suoyang Ancient City (Appendix B). Within the workshop, participants undertook discussions and completed a co-created questionnaire on: (i) the values of Chinese earthen heritage, (ii) factors that needed to be considered when designing a conservation strategy for Chinese earthen heritage and (iii) the relative importance of different aspects of a conservation strategy.

Results showed that heritage experts based in both China and the UK viewed the historical value of Chinese earthen heritage as most important, with its scientific and cultural value also of importance. In addition, results also showed that both groups of experts viewed the need to maintain the authenticity and integrity of the site as highly important. They expressed strong preferences for conservation strategies to:

- (i) be underpinned by scientific research;
- (ii) be applied at a site scale;
- (iii) modify the environment rather than being applied to the site's historic material;
- (iv) reduce deterioration over a 50+ year timeframe; and
- (v) require minimal maintenance costs.

In addition, the heritage experts based in China expressed a preference for the conservation strategy to not be visible whereas those based in the UK showed a preference for the conservation strategy to be visible.

This suggests that current conservation strategies, such as the application of consolidants, do not fully meet the requirements of the heritage experts based in either China or the UK. Consequently, research is needed into new conservation approaches

for earthen heritage that reduce deterioration rates by modifying the environment and that can be applied over whole sites.

Given complex heritage-environment interactions, this alternative approach requires both a full understanding of how multiple environmental processes interact with each other around heritage sites and also how environmental processes cause deterioration to earthen heritage. If both sets of processes are not fully understood, conservation strategies could result in unintentional increases in deterioration, as illustrated by the construction of some shelters (Aslan, 1997; Matero, 1999).

See Appendix B for the full, published version of the paper.

2.6 Earthen heritage research challenges

Earthen heritage research has been undertaken using a range of methods. Table 2.4 shows how earthen heritage research has investigated a wide range of topics including environmental drivers of deterioration, material properties and the impact of additives and structure additions on earthen materials. This has been achieved using laboratory, field, modelling and environmental methods. Table 2.4 also shows how a range of historic and modern materials have been used in research. However, each method has its own set of challenges that are discussed below.

Table 2.4: Methods used in rammed earth, earthen heritage studies according to their purpose of research. ‘^’ = Multiple methods used within the study; ‘*’=The study had multiple purposes. ‘HistM’= Historic Material taken directly from site for testing; ‘LabHistM’ = Samples prepared in the laboratory using historic material; ‘LabOth’ = Samples prepared in the laboratory using other material such as freshly sources soils; ‘TWall’ =Test walls located both in the field and laboratory; ‘Site’ = Measurements taken on site.

Purpose of study									
Environmental drivers of deterioration			Material characterisation and properties		Impact of additives on earthen material		Impact of structural additions to earthen material (including mortar)		
Loc	Study	Material(s) used	Loc	Study	Material(s) used	Loc	Study	Material(s) used	
Laboratory experiments	CHN Mao et al. (2008)*	LabHistM	CHN Wu et al. (2012)	HistM	AUS Beckett and Ciancio (2016)	HistM	CHN Zhang et al. (2015)^	LabHistM	
	X. D. Wang et al. (2010)*^	LabHistM	X. Wang et al. (2019)	LabOth	Arrigoni et al. (2017)	LabOth		Site	
		Site	ESP Lombillo et al. (2014)	LabOth	CHN X. D. Wang et al. (2010)*^	LabHistM	Zhang et al. (2017a)^	LabHistM	
	Kai et al. (2012)	LabHistM		TWall		Site		Site	
	Shao et al. (2013)^	LabHistM	Gutierrez-Carrillo et al. (2019)^	HistM	Mao et al. (2008)*	LabHistM	Wang et al. (2020)	LabHistM	
		Site		Site	Mao et al. (2015)*	LabHistM	PRT Gomes et al. (2016)	HistM	
	Mao et al. (2015)*	LabHistM	Martín-del-Rio et al. (2019)	HistM	Yuan et al. (2016)*	LabHistM	Silva et al. (2018)	LabHistM	
	Yuan et al. (2016)*	LabHistM	FRA Bui et al. (2015)	HistM	Zhao et al. (2016)^	HistM		TWall	
	Pu et al. (2016a)^	HM		LabHistM	Pu et al. (2016a)*^	HistM	Gomes et al. (2019)*	LabHistM	
		Site		TWall		Site	N/A Fagone et al. (2019)	LabOth	
	Pu et al. (2016b)*^	LabHistM	Hamard et al. (2017)	HistM	Zhang et al. (2017b)	LabOth			
	Du et al. (2017)^	HistM	KOR Jo et al. (2018)	HistM	Lu et al. (2018)	LabOth			
		Site	MAR Gamrani et al. (2012)	HistM	Pei et al. (2020a)	LabHistM			
	Zhang et al. (2018)^	LabHistM	Daoudi et al. (2018)	HistM	ESP Pei et al. (2020b)	LabHistM			
		Site	PRT Gomes et al. (2014)	HistM	ITA Elert et al. (2015)	LabHistM			
	(Cui et al., 2019b)^	HistM	Mateus et al. (2019)	HistM	IRN Arrigoni et al. (2019)	LabOth			
		Site	Parracha et al. (2019)	LabHistM	N/A Hussaini and Toufigh (2019)	LabHistM			
	(Cui et al., 2019b)^	HistM	Gomes et al. (2019)*	HistM	Khadka and Shakya (2016)	LabHistM			
		LabHistM	TUR Arslan et al. (2017)	LabOth					
	JPN Liang (2018)	LabHistM		TWall					
	N/A Rempel and Rempel (2019)^	LabOth	N/A Bui et al. (2011)	LabOth					
			Q. B. Bui et al. (2014)	LabHistM					
				TWall					
			Reyes et al. (2018)	TWall					

Field tests	CHN X. D. Wang et al. (2010)*^	LabHistM	CHN Wang et al. (2016)	Site	CHN X. D. Wang et al. (2010)*^	LabHistM	CHN Zhang et al. (2015)^	LabHistM
	Sun et al. (2011)	Site	ESP Gutierrez-Carrillo et al. (2019)^	HistM		Site		Site
	Shao et al. (2013)^	LabHistM	FRA Bui et al. (2009)*	TWall	Zhao et al. (2016)^	HistM	Zhang et al. (2017)^	LabHistM
	Huang and Peng (2015)^	Site	MAR Bakadi et al. (2020)	Site	Pu et al. (2016b)*^	LabHistM		Site
Modelling	Pu et al. (2016a)^	HistM	PRT Faria et al. (2012)	TWall	ESP Elert et al. (2019)	LabHistM		
	Pu et al. (2016b)*^	LabHistM				TWall		
	Cui et al. (2017)^	Site						
	Du et al. (2017)^	HistM						
Environmental	Zhang et al. (2018)^	LabHistM						
	Luo et al. (2019)^	Site						
	(Cui et al., 2019b)^	HistM						
	FRA Bui et al. (2009)*	TWall						
Other	N/A Zhu et al. (2018)	Site						
	CHN Shi et al. (2014)^	Site	N/A Nowamooz and Chazallon (2011) (LabOth)				N/A Angulo-Ibáñez (2017) (Site)	
	Huang and Peng (2015)^	Site	N/A Bui et al. (2016)	(TWall)			N/A Bui et al. (2019)	(Site)
	Peng et al. (2015)^	Site						
Other	Du et al. (2017)^	LabHistM						
	Luo et al. (2019)^	Site						
	N/A Rempel and Rempel (2019)^	LabOth						
	CHN Shi et al. (2014)^	Site						
Other	Peng et al. (2015)^	Site						
	Cui et al. (2017)^	Site						
	(Cui et al., 2019b)^	HistM						
	N/A Rempel and Rempel (2019)^	LabHistM						
Other	CHN (Cui et al., 2019b)^	Fuzzy analytic hierarchy process	ESP Gutierrez-Carrillo et al. (2019)^	Archives	CHN Pan et al. (2020)	Review	CHN Pan et al. (2020)	Review

2.6.1 Laboratory methods

Laboratory studies have commonly been used in earthen heritage research to investigate the deteriorative impact of specific environmental drivers under controlled conditions. Laboratory methods such as accelerated erosion, drip and freeze thaw tests, have been used to assess the durability of earthen materials in specific environmental conditions (Beckett et al., 2020; Mao et al., 2015); after the application of a surface conservation treatment (Beckett and Ciancio, 2016; La Russa et al., 2019; Shao et al., 2013; Y. Zhang et al., 2016); and with structural additions such as wooden rods (Bui et al., 2019; Gomes et al., 2019). Laboratory methods allow samples to be subjected to accelerating ageing or deterioration processes at a higher than naturally occurring magnitude/frequency to simulate deterioration over longer time periods than is feasible in the field (Binda et al., 1995; Mao et al., 2015). However, uncertainties over how reflective these processes are of natural ageing have been raised, with some arguing that they are only reflective of deterioration which occurs in extreme events (Beckett et al., 2020).

Further difficulties can arise in relating laboratory findings to earthen heritage sites. The samples used in laboratory studies tend to be small and are exposed to environmental drivers for a very short amount of time in comparison to the lifespan of many heritage sites (Bui et al., 2015; La Russa et al., 2019; Mao et al., 2015, 2008; Y. Zhang et al., 2016). Consequently, these studies can face upscaling issues when relating findings taken from small blocks, measuring an order of centimetres, over a period of weeks to months, to heritage sites which span hundreds of meters and have been exposed to environmental conditions for hundreds of years (Beckett et al., 2020; Viles, 2001).

2.6.2 Field-based methods

Undertaking research at earthen heritage sites removes many of the scaling-up issues faced in laboratory experiments. Field-based methods allow the complexity of interactions between earthen heritage and the environment to be captured, providing a holistic understanding of deterioration processes occurring at a specific site. For example, at Jiaohe Ancient City, China, multiple field campaigns enabled the interactions between wind, water, temperature and chemical related deterioration processes to be identified (Z. Li et al., 2011; Shao et al., 2013; Sun et al., 2011; Y. Zhang et al., 2016; Zhao et al., 2012).

However, understanding these interactions can be highly challenging, especially if the site does not have comprehensive environmental records. Without environmental records, abductive reasoning is required to infer a causal mechanism back from the resultant deterioration feature. In cases where multiple processes are able to form the deterioration feature, issues of equifinality can arise (Beckett et al., 2020; Haines-Young and Petch, 1983). In addition, understanding the long term impact of many environmental processes on earthen heritage deterioration is still hampered by the relatively short research history of earthen heritage in comparison to Western building materials, such stone or brick (e.g. Loughlin, 1931; Schaffer, 1932). Few longitudinal studies aimed at monitoring earthen deterioration have been conducted over periods lasting more than a few years (e.g. Bui et al., 2009). As such, field experiments tend to capture a snap-shot of current deterioration processes influenced by the past deterioration. Consequently, all field studies need to reflect on the processes which they record and over what time scales.

Furthermore, there are many challenging practical and financial implications associated with undertaking field-based research. Firstly, permission to access and work on the earthen site has to be granted (ICOMOS China, 2015). As heritage sites tend to be of high importance, negotiating permissions can be lengthy, especially if this has to be undertaken in a non-native language and through a non-familiar political system.

Secondly, many earthen sites are located in remote locations with harsh environmental conditions (L. Li et al., 2011; WHEAP, 2012). This means that any fieldwork can be highly expensive both in terms of capital and time. Consequently, the total number of visits within which data can be collected may be limited. These time-short situations can result in little flexibility for re-doing experiments or trialling different equipment should something prove to be faulty or inadequate. The remoteness can also mean that on-site services can be limited and so all equipment has to be taken with the researcher. If any equipment requires electricity or water, additional costs for transporting (as well as having the relevant knowledge for using) kit such as a generator, petrol and water barrels have to be factored in.

Importantly, field-based methods also have to be aware of any damage the data collection processes could cause to the heritage site (English Heritage, 2008; ICOMOS China, 2015). Whilst, in some cases, permission to collect sampling may be provided, this cannot be assumed and, in most cases, non-destructive methods will need to be used. Given the weak nature of earthen materials, methods that are classified as non-destructive or micro-destructive on stone and are commonly applied to Western style heritage buildings (e.g. surface hardness tests using a piccolo or equotip) may cause visible damage to earthen material and therefore would not be suitable for earthen heritage sites (Mol, 2016; Wilhelm et al., 2016). Consequently, the number of potential

methods that can be utilised for earthen heritage this can be severely limited, resulting in researchers having to re-purpose methods and imaginatively design experiments to ensure that the methods applied are suitable.

The construction of test walls at earthen heritage sites can provide a valuable research resource to overcome some of the issues associated with field experiments (Figure 2.4). Test walls can be exposed to the same complex environmental conditions as the heritage site but also be tested using methods that can result in the removal of material from the parent body.

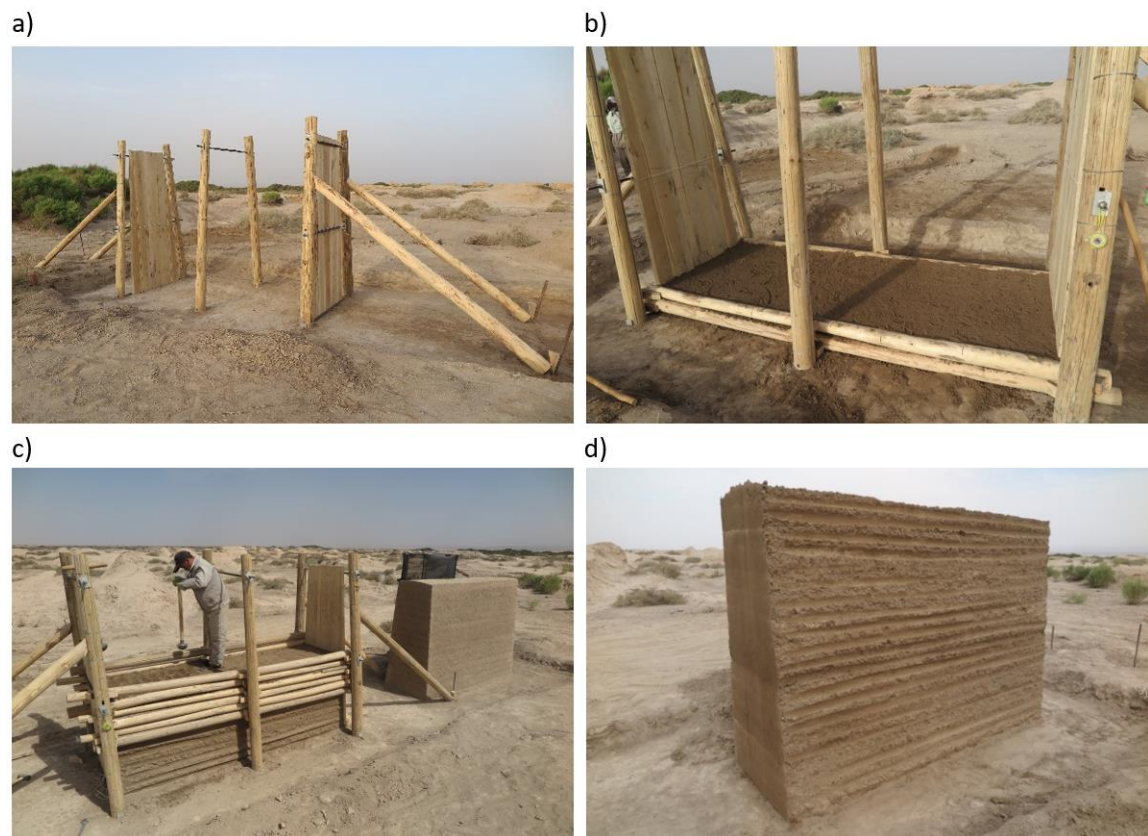


Figure 2.4: The test wall construction process: a) setting the forms, b) layering the soil, c) ramming the soil layer, d) the finished wall. Photo credits: Dunhuang Academy.

However, test walls are expensive and time consuming to construct and need several months (preferably > 6 months) to cure in the natural environment. Consequently, the construction of earthen test walls has to be undertaken within the scope of a long-term

research project and cannot be feasibly built within the timeframe of a DPhil/PhD. Pre-built test walls can be re-purposed but studies have to accommodate the original material make-up and/or dimensions of the wall which can constrain the experimental set up. In addition, if the test wall is used for an experiment that results in material loss, there may be constraints on the amount of test runs that can be undertaken to ensure that future research can also utilise the same test wall. It should also be noted that as test walls are generally orders of magnitude younger than historic material, results can still suffer from upscaling issues if extrapolating results from the test walls to the historic walls (Oliver, 2008; 2000).

2.6.3 Modelling

Earthen heritage research has predominantly been undertaken using field or laboratory experiments, with comparatively few studies employing modelling methodologies (Table 2.4). Studies that have employed modelling have generally either used: (i) conceptual models to link deterioration processes with specific deterioration patterns such as gullyng and scaling off (Cui et al., 2019a; Du et al., 2017); (ii) numerical models to assess rates of deterioration (Luo et al., 2019; Peng et al., 2015; Rempel and Rempel, 2019); or (iii) structural models to compare the stability of earthen walls comprised of different earthen materials (Nowamooz and Chazallon, 2011) or with structural reinforcements (Angulo-Ibáñez, 2017; Bui et al., 2019). These models enable interactions between multiple processes to be investigated without posing any risk to the historic material and enabling conservation practices to be better informed. However, several of these models such as Luo et al.'s (2019) model of wind and rain deterioration at the Fujian buildings, China, are not spatially explicit and so do not capture the variability in deterioration seen at many earthen heritage sites (Shao et al., 2013). In addition, the

variability of deterioration seen at earthen heritage sites is not captured in many models, due to the limited spatial scale of the models. For example, in Angulo-Ibáñez (2017) and Nowamooz and Chazallon (2011) only single walls or wall joints are modelled.

In other disciplines, models have been used to provide results that are outside of the immediately observable (Lane, 2010) by capturing the impact of multiple environmental processes on a given object or landscape (Buckland et al., 2019; Huinink et al., 2004; Murray and Paola, 1994; Smith, 1991); assessing environmental processes over spatial and temporal timescales that are not feasible in the field (Bonnet and Crave, 2003; Messenzehl et al., 2017); and testing the impact of extreme situations which may not be feasible or ethical to test in reality (Oliver, 2008; Wolfram, 1984).

However, capturing environmental interactions over large spatial and temporal scales is highly computationally expensive. Computational models such as computational fluid dynamic (CDF) models have previously been used for heritage conservation (e.g. D'Agostino et al. 2014; Stoyanov et al. 2010; Iyer-Raniga & Wong 2012; Kris et al. 2001; Eriksen et al. 2016) but have generally been applied to indoor heritage environments (Albero et al., 2004; Corgnati and Perino, 2013; D'Agostino et al., 2014) where the spatial scale of the model is much smaller and therefore the computational expense is justifiable (D'Agostino et al., 2014; Mayaud et al., 2017a; Osanyintola and Simonson, 2006; Papakonstantinou et al., 2000). To capture the interaction of environmental processes at earthen heritage sites over long (multi-decadal) time periods, a computationally efficient model which can spatially resolve multiple processes is needed. In landscape dynamic studies, cellular automaton (CA) models have been used

to simulate the development of given landforms (Figure 2.5), such as dunes, alluvial fans and river channels, in a spatially specific manner (Coulthard et al., 2002; Grimm et al., 2005; Mayaud et al., 2017a; Murray and Paola, 1994). Consequently, applying CA modelling to earthen heritage would enable the impact of complex, interacting environmental processes over large spatial and temporal scales, and its impact on earthen deterioration, to be captured.

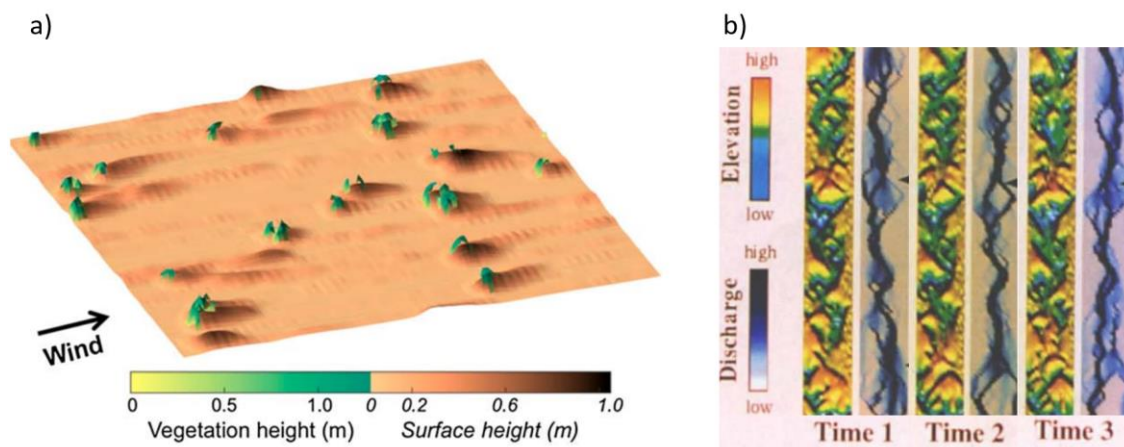


Figure 2.5: Examples of outputs from cellular automaton models: a) showing the development of nebkha dunes and b) showing the development of braided rivers. Images are adapted from Mayaud et al. (2017) and Murray and Paola (1994), respectively.

2.7 Aim and objectives

In this thesis, I aim to determine the likely impacts of the main environmental drivers of earthen heritage deterioration under current and potential future conditions in dryland regions.

The thesis will address this aim with the following objectives:

Objective 1: Assess the deteriorative impact of key individual environmental processes in the field (Paper 1).

Objective 2: Evaluate the relative importance of wind and rain in driving deterioration at an earthen heritage site (Paper 2).

Objective 3: Create an analytical framework that combines and evaluates the risk of multiple environmental drivers of deterioration pose to earthen heritage (Paper 3).

Objective 4: Determine the risk posed by environmental drivers of deterioration to earthen heritage under a range of future climate scenarios and conservation strategies (Paper 4).

By investigating the deteriorative impact of environmental drivers, I intend to:

- (i) contribute to the field of earthen heritage research by examining the complex interactions between the environment and earthen material; and
- (ii) inform practical conservation for earthen heritage sites by developing a framework that can aid the conservation decision-making process.

Therefore, my findings in this thesis are intended to be relevant to both a range of researchers in an academic setting (i.e. earthen heritage researchers, geomorphologists, heritage scientists) and heritage practitioners who work at a range of earthen heritage sites in dryland regions.

3 Research framework and methods

3.1 Overarching framework

This thesis uses a framework that combines field data and modelling to examine: i) how environmental drivers cause deterioration at earthen heritage sites; and ii) how the risk of deterioration may change under future conditions. Fieldwork allows site-specific data to be collected, ensuring empirical validity, while modelling enables relationships between the environment and earthen heritage deterioration to be tested under conditions that differ from the present (Lane, 2010; Oreskes et al., 1994). Together they provide a powerful approach for understanding and investigating complex, interacting systems that has been commonly used in both environmental and heritage science research (see Table 3.1 for examples).

Table 3.1: Examples of environmental and heritage science fields of research that have used a framework that combines field data and modelling

Environmental Science		Heritage Science	
Topic	Examples	Topic	Examples
Dune formation	Schwämmle and Herrmann (2005) Baas and Nield (2007) Nield and Baas (2008a) Narteau et al. (2009) Zhang et al. (2010) Mayaud et al. (2017a)	Moisture ingress	Kumaraperumal et al. (2006) Erkal et al. (2012) Luo et al. (2019)
Slope stability	Harris et al. (2001) K. Zhang et al. (2016) Messenzehl et al. (2017) Negi et al. (2020)	Structural resilience to earthquakes	Cuadra et al. (2008) Kim and Park (2014) Hanazato et al. (2016) Micelli and Cascardi (2020)
Vegetation change	Dunkerley (1997) Balzter et al. (1998) Baas (2002) Bailey (2010) Marques et al. (2020)	Pollutant contamination	Grau-Bové et al. (2016) Grau-Bové et al. (2019)

In theory, the relationship between field data and modelling is circular and iterative, with field data informing model development and model results informing data collection in the field (Figure 3.1). In practice, research often starts with either field data or modelling depending on the availability of data or a previously developed or adaptable model. Starting with modelling enables previous assumptions or hypotheses in the literature to be tested against the field data. This approach traditionally requires a pre-existing understanding of the fundamental drivers of the system, with dominant processes being quantified and parameterised - although advances in fields such as artificial intelligence methods mean that some models can be inputted with unexplored data to produce hypotheses (Lecun et al., 2015; Schmidhuber, 2015).

Currently, in earthen heritage research, there is limited data on how environmental processes drive deterioration. Therefore, this research begins with fieldwork, to collect data on how environmental processes interact with, and cause deterioration to, earthen heritage sites over multiple spatial and temporal scales (Papers 1 and 2). This field data is then used to inform model development (Paper 3), enabling the impact of potential conservation strategies and predicted future climates to be tested (Paper 4).

Conservation strategies found to be the most effective by the model should be trialled in the field before implementation across a site and then regularly monitored after implementation.

Figure 3.1 shows (i) how the four papers presented in this thesis map onto the field data-modelling research framework; and (ii) how findings feed into subsequent papers.

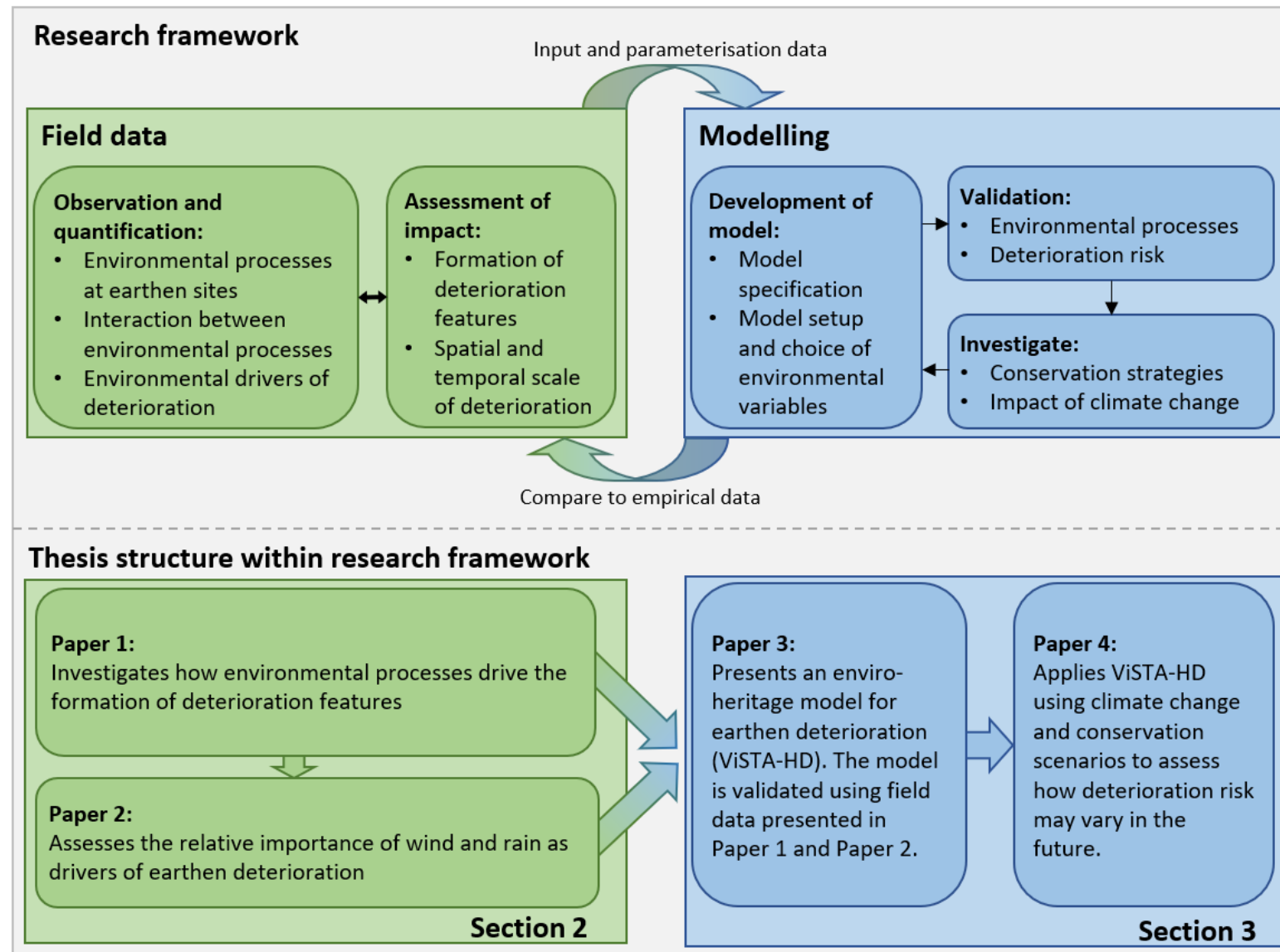


Figure 3.1: Research framework used in this thesis

Research in this thesis has focused on deterioration processes occurring at the site of Suoyang Ancient City, 锁阳城, hereafter known as Suoyang. Focusing research at one heritage site enabled the complexity of interactions between environmental drivers of deterioration and earthen heritage to be comprehensively studied. Given the density of earthen sites in northwest China and central Asia built using similar materials and techniques as Suoyang, findings presented in this thesis are presumed to be representative of deterioration processes occurring at many of the earthen heritage sites in this area, as well as sites in other dryland regions. This is discussed in greater depth in Section 8.5.

3.2 Field site: Suoyang Ancient City

Suoyang is an archaeological site built from rammed earth in the Han (206 BC–220 AD) and Tang (618 – 907 AD) dynasties (Li and Xie, 2011; UNESCO, 2014). It is one of 33 sites that form the Silk Roads World Heritage Listing and was included because it is an exceptional example of a fortification and communication settlement. The site is managed by the Guazhou Museum, a Government Institution of Guazhou County, Gansu Province, China. Conservation advice is provided by research groups including those affiliated with the Dunhuang Academy, Dunhuang, Gansu Province, China.

Suoyang is located in the semi-arid Hexi corridor in Guazhou County, Gansu Province, northwest China (Figure 3.2a; 40°14'47"N, 96°12'11"E), on Cenozoic strata between the Sanweishan and Altyn Tagh fault lines (Figure 3.3). The Hexi Corridor runs northwest from the Yellow river, north of the high Qilian Mountains and south of the Gobi Desert and grasslands of Outer Mongolia. This corridor was an important route for trading: the

ancient Silk Road was established through this region due to the presence of a string of oases in an otherwise harsh dryland environment (UNESCO, 2016).

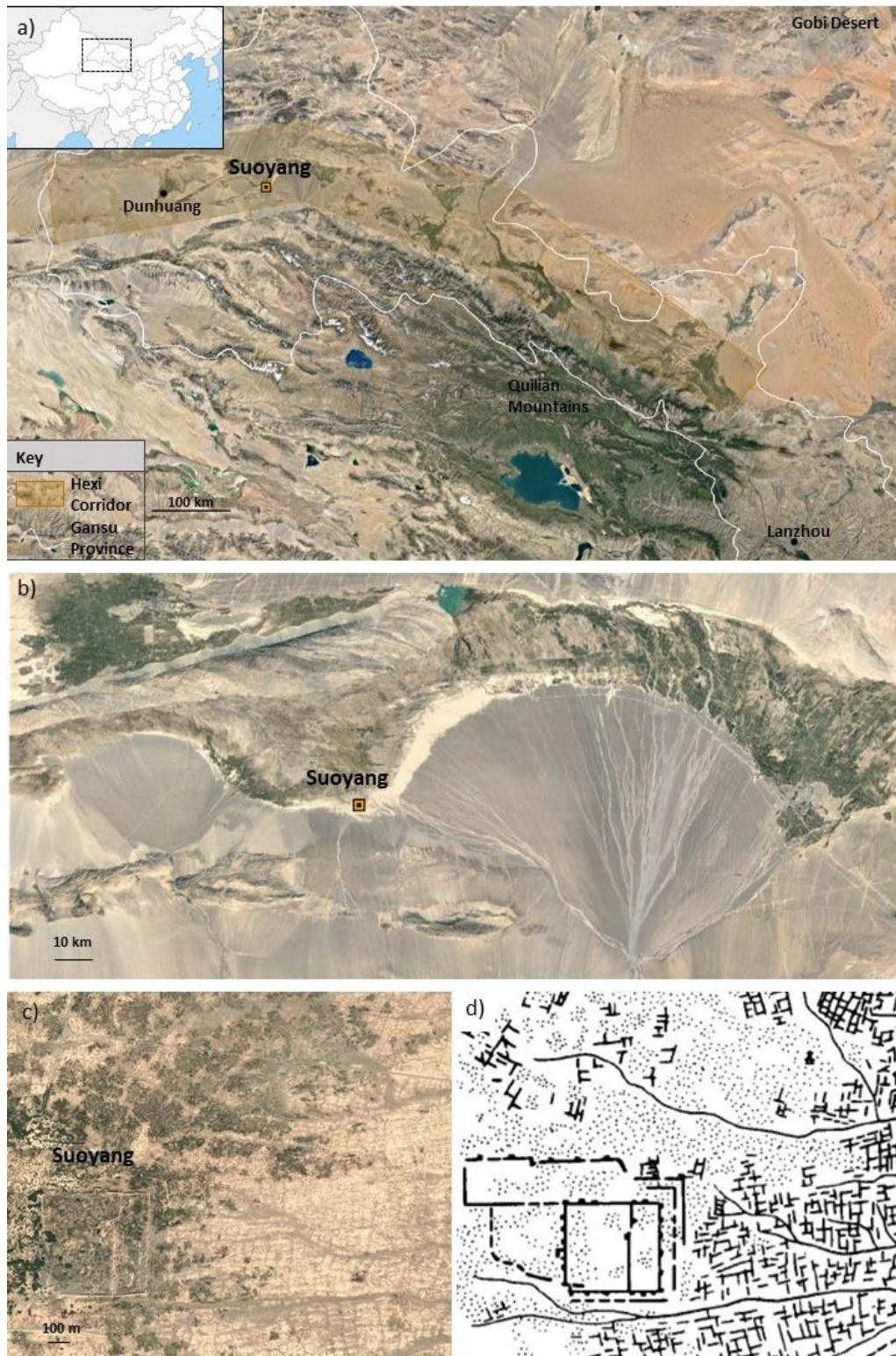


Figure 3.2: The site of Suoyang Ancient City. Its location: a) in the Hexi Corridor northwest China; and b) to the west of an alluvial fan forming to the north of the Qilian Mountains (credit: Google Earth). The Inner City walls are shown in c) and d) a sketch map shows the key wall and irrigation features (provided by the Dunhuang Academy).

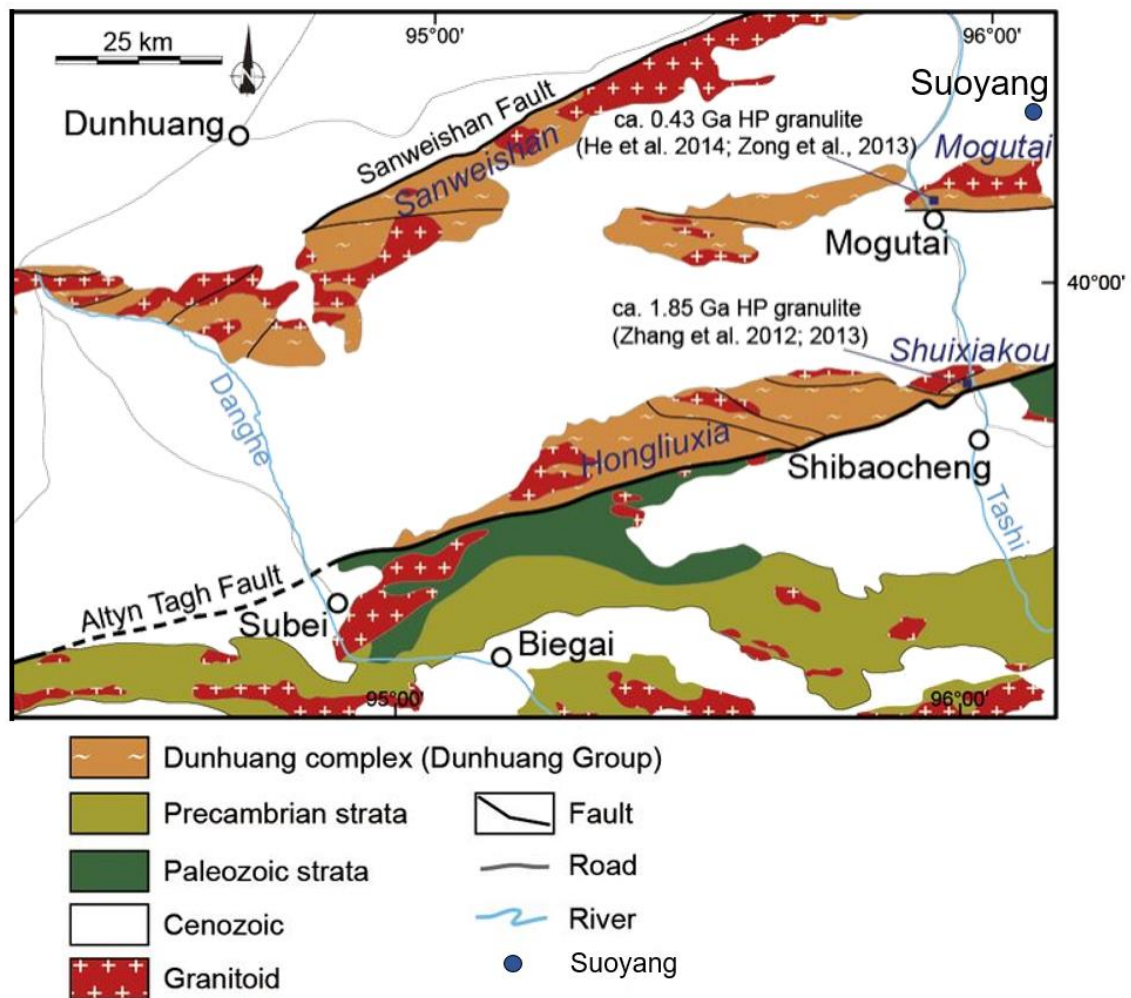


Figure 3.3: A geological map of the area around Suoyang. Adapted from Wang et al., (2016).

Within the Hexi Corridor, the site of Suoyang is located to the west of a large alluvial fan, which forms northwards from the Quilian Mountains (Figure 3.2b). The built areas of the site covers several square kilometres with its elevation ranging from approximately 1350 to 1370 m above sea level. Suoyang consists of an inner city wall which bounds a roughly 500 m² area (Figure 3.2c); outer city walls; houses; stables; archery platforms; an extensive ancient irrigation network; and a Buddhist monastery that has links to other Buddhist sites in the area (Figure 3.4). The inner city walls and the monastery are the best preserved structures. The height of the inner city walls range from a meter in the most deteriorated sections to over 20 meters in the best preserved sections (UNESCO,

2014). Diagrams of the site during occupation are not currently available and further archival research is needed to address this.

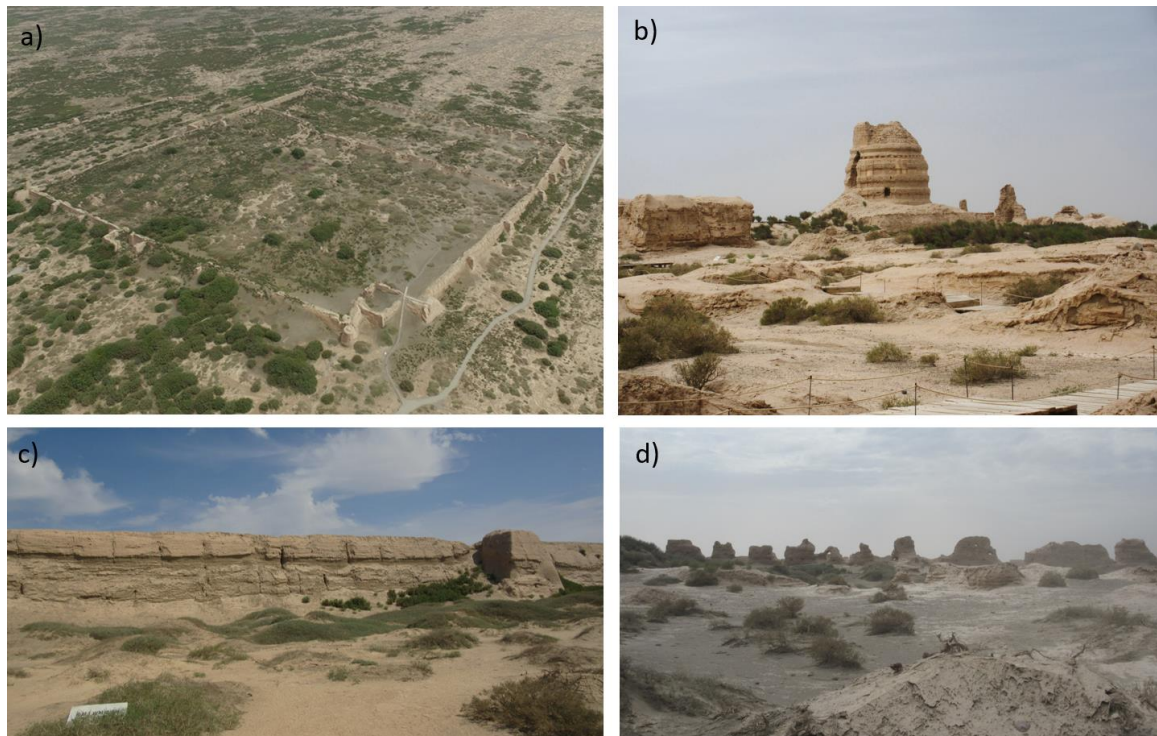


Figure 3.4: a) An aerial view of Suoyang (credit: Dunhuang Academy), b) the Buddhist monastery located northeast of the inner city walls, c) a section of the southern inner city wall with fortress tower and d) a heavily deteriorated section of the east inner city.

During the city's occupation, an irrigation network that diverted water from the Shule River to > 60 km² of land to south and east of Suoyang (Figure 3.2d), forming an agricultural system that sustained Suoyang when it was occupied (UNESCO, 2014). In addition to the plant-based agriculture, animals including sheep, goats and horses were kept in enclosures outside the inner city walls (Dunhuang Academy, Pers. Comm. Aug 2018). Remains of houses (short wall sections) can be found both inside and outside the inner city walls (UNESCO, 2014).

Suoyang's westerly location meant the city operated as one of the last outposts for traders going west but also acted as one of the main defensive centres against any invaders coming from the east (UNESCO, 2014). The presence of both Inner and Outer City walls, as well as the defensive turrets built around the city walls suggests Suoyang

was viewed as an important town providing safety for the region. It is known to have housed the Western Xia army just before the site was abandoned (UNESCO, 2014). The site was abandoned approximately 400 years ago due to a decline in trade along the Silk Road and because the Shule River avulsed away from the city (Xie et al., 2007a). Further research is needed to determine Suoyang's role in specific wars or uprisings.

Today, Suoyang is located approximately 150 km from the town of Dunhuang and 1000 km from Lanzhou, the capital of Gansu Province (Figure 3.2a). Visitor numbers to the site are relatively low (12,000 visitors in 2017) but these are expected to increase as transport links to the site are improved (Dunhuang Academy, unpublished). For comparison, the Mogao Grottoes, located outside Dunhuang, receive 20,000 visitors a day during their peak summer season (Dunhuang Academy, Pers. Comm. Aug 2017).

A range of vegetation is found around the site (Figure 3.5). The vegetation is comprised predominantly of hardy shrub species with *Alhagi sparsifolia* and *Nitraria tangutorum* dominating around the Inner City walls and to the east of the site. Some grassy patches are also found but no trees were present.

Suoyang is subjected to harsh climatic conditions and is located in a cold desert environment. Summer temperatures exceed 40°C while winter temperatures fall below -30°C (Figure 3.6). On average, the site receives 49 mm of precipitation in sporadic rainfall events commonly associated with storms (Figure 3.6). However, as with many dryland regions, rainfall is highly variable (Wang et al., 2013) with the annual precipitation varying between 33 mm and 74 mm between 1986 and 2005 (Dunhuang Academy, unpublished). In addition, the site is exposed to strong, sediment carrying winds especially in summer months.

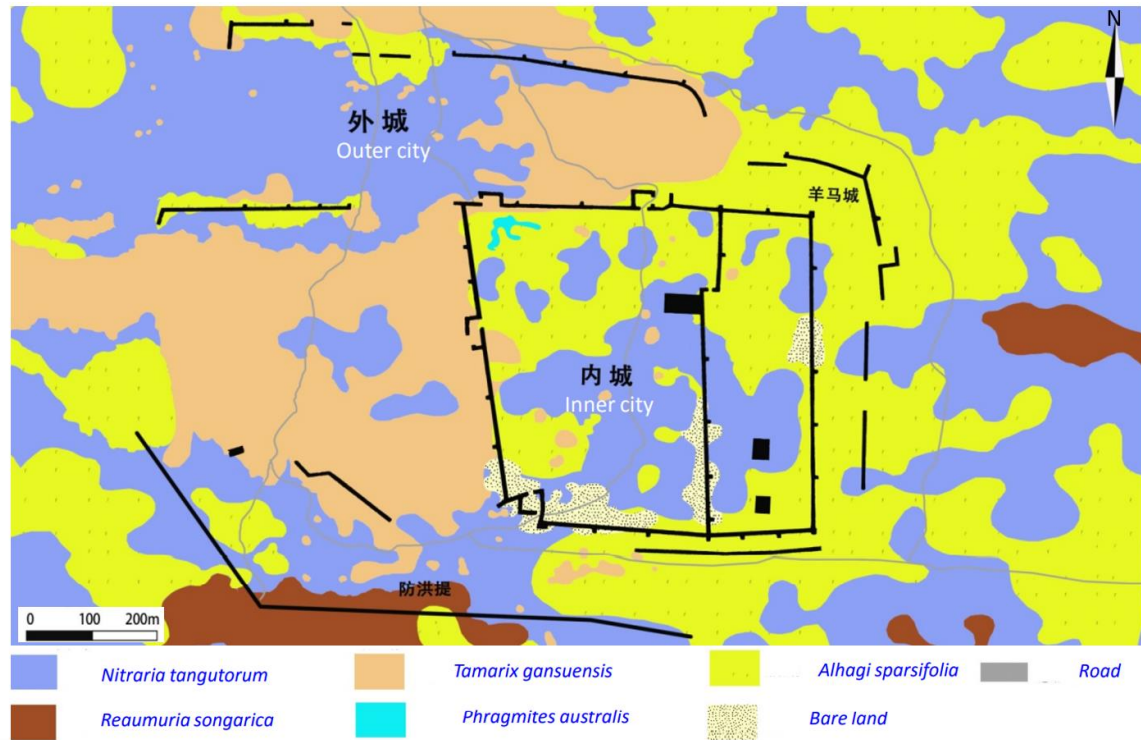


Figure 3.5: The dominant vegetation species found at Suoyang. Credit: Dunhuang Academy.

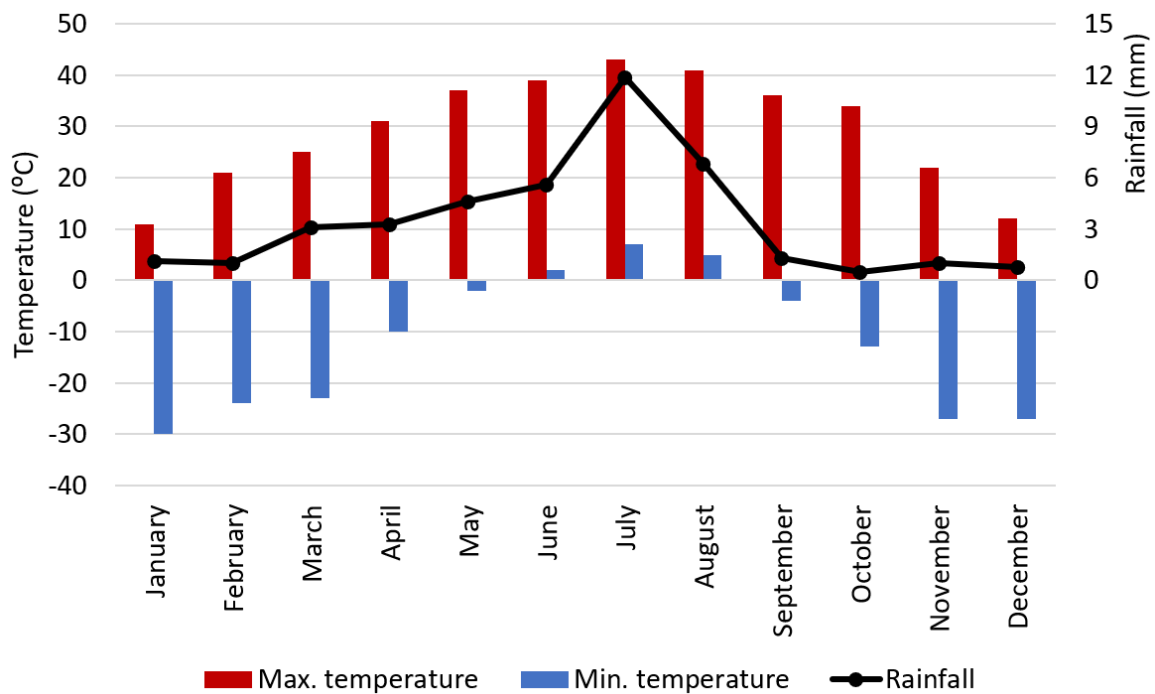


Figure 3.6: Mean monthly maximum and minimum temperatures (°C) and mean monthly rainfall (mm) for Guazhou county. Climatic data (unpublished) was provided by the Dunhuang Academy for the period 1997-2007 (temperature) and 1995-2005 (rainfall).

Over the last millennium, data from juniper and pine tree rings show that north-west China has experienced variations in climate driven by the changing strength of the Asian monsoon (Yang et al., 2011; Fang et al, 2012; Chen et al., 2013; Sun et al., 2013). During weak phases (e.g. in the mid to late 1400's; mid 1600's to mid 1700's; and mid 1900's) the region experienced relatively dry periods, while in strong phases (e.g. in the 1500's; and mid 1800's to early 1900's) average rainfall increased by as much as 50% (Yang et al., 2013). In addition, during these periods of aridity, the frequency of dust storms in arid and semi-arid regions of China increased caused by increases in strong winds and increased sediment availability (Xu, 2017).

Suoyang's location between the two fault lines means the threat from seismic activity is high. Research from the Mogao Grottoes, located 150 km to the west of Suoyang and managed by the Dunhuang Academy, has suggested that the Sanweishan Fault could trigger a magnitude 6.5 to 8 earthquake (Jinshi, 1997; Iwasaki et al., 2016), which would likely cause extensive damage to Suoyang. Given the active nature of the faults, Suoyang is likely to have been subjected to seismic events since construction but damage from such events is not obvious at the site. Further surveying is needed to record potential seismic damage from such events.

Suoyang's exposure to drivers of deterioration has resulted in the formation of features, such as pitting, flaking, gullying, cracking, slumping and wall collapse (See Appendix E for Glossary and Atlas). These features are a product of historical and on-going processes. Given the lack of data about environmental and seismic history for the site, determining the specific drivers of deterioration is highly complex. This research focuses on the role of environmental drivers of deterioration given the demand for conservation strategies

that minimise future environmental impacts of deterioration on earthen heritage sites. I discuss some of the issues regarding inheritance of deterioration processes in Chapter 5, but further research is needed - especially on the impacts between seismic and environmental deterioration processes.

At Suoyang, conservation strategies have been applied at the site including the formation of a flood defence barrier to protect against flash flooding (Xie et al., 2007a); the application of consolidant treatment on limited sections of the inner city walls; and the prevention of farming in the local area (UNESCO, 2014). The prevention of farming has resulted in the grazing of local livestock such as goats being prohibited in the site's buffer zone. However, despite these interventions, deterioration is still occurring at the site and a clear long term, site scale conservation strategy is lacking.

3.2.1 Experimental area

In 2015, an experimental area was established by the Dunhuang Academy at Suoyang, to the east of the inner city walls. The experimental area was built as part of attempts to improve understanding of deterioration and potential conservation strategies at Suoyang. In the experimental area, a small and large set of test walls have been built using traditional methods to mimic the material characteristics and building techniques of Suoyang (Figure 3.7).

a)



b)



Figure 3.7: The tests walls located at Suoyang in the experimental area. a) The small test wall with the section of the test wall used in this research indicated with a red arrow and b) the large test walls.

The small set of test walls was built in April 2015 and is comprised of seven sections (Figure 3.7a). It was originally designed to test the material characteristics of rammed earth when different additives had been mixed with the loessic soils. Permission was granted to use a section of this wall for this research. Experiments were only allowed to cause limited damage to the test wall to ensure that future research would also be able to benefit from the resource. As only one wall section did not have additional additives, and as Suoyang was built predominantly without additional additives, only the non-additive section measuring 64 cm high, 76 cm wide and ~50 cm deep, was used in the experiments (Figure 3.7a shown with an arrow).

The set of four large test walls, each measuring 2 m high, 3 m wide and 1 m deep, was constructed in 2017 (Figure 3.7b). The walls were built in partnership between Oxford University and the Dunhuang Academy, as part of a project looking at nature-based solutions for earthen heritage conservation, funded by the Royal Society International Exchange Grant (Grant number: IE151144). Two of the large test walls were built with a density of 1.75 g cm^{-3} and two with a density of 1.65 g cm^{-3} representing a non-deteriorated and a deteriorated state, respectively. The size and position of these test walls enabled us to use them to understand how environmental processes interacted with and around earthen structures. Due to an ongoing project studying the natural deterioration of these test walls, these walls could be used for observation but we were not able to use them for active deterioration experiments.

The test walls at Suoyang enabled research to be undertaken on earthen heritage structures without causing any damage to the historic structure. However, these walls are modern structures and so lack the material maturity of the historic walls. By being

young structures, the test walls are likely to still be drying out meaning that an uneven distribution of internal moisture content is likely to be present, which could also impact the distribution of salts within the structure (Shen et al., 2017). Furthermore, materials used to build the test walls were new and will have some differences with those used that were used to build the historic structure (Dunhuang Academy, unpublished). As a result, the material properties of the test walls are likely to vary from the historic walls, despite best efforts to match specific properties such as particle size distribution and dry density. Consequently, comparing deterioration results from test and historic walls needs to be done with consideration of limitations caused by the immaturity of the test walls.

3.2.2 Site visits

Two fieldtrips were undertaken as part of this research in August 2017 and August 2018, respectively. The first trip involved a pilot visit to Suoyang, viewing available equipment and meeting researchers at the Dunhuang Academy. The second visit involved an intensive ten-day fieldwork campaign.

The fieldwork was timed to coincide with the windiest time of year when Suoyang is subjected to strong easterly winds, ensuring that wind flow and sediment transport data could be collected. For the duration of the field trip, the Dunhuang Academy provided: access to the historic site of Suoyang and the experimental area; all equipment required in the field; and a team of researchers to help with data collection.

3.3 Field-based methods

A multi-method approach was used to collect data in the field (Figure 3.8), drawing particularly on research methods used in earthen heritage (Mao et al., 2015; Shao et al., 2013), and aeolian geomorphology studies (Goossens and Offer, 2000; Mayaud et al., 2017c; Tan et al., 2016). Field data was collected on (i) the drivers of deterioration and (ii) interactions between earthen heritage and the environment. The drivers of deterioration, and the resulting deterioration features, were assessed using a controlled deterioration field experiment on the small test wall and visual analysis deterioration surveys on both the test and historic walls (Chapters 4 and 5).

Focus of study		Methods			
		Small test walls	Historic Walls	Large test walls	Modelling
Drivers of historic deterioration	Environmental drivers of deterioration	Wind, sediment and rainfall erosion tests			
	Deterioration features				
Enviro-heritage interactions	Wind flow patterns				
	Wind speed recovery				
	Sediment transport			Sediment trap transect	
Drivers of future deterioration	Deterioration risk				VISTA-HD
Application of methods to papers		Paper 1 and 2	Paper 2	Paper 2	Paper 3 and 4

Figure 3.8: Summary of methods used in this thesis to address earthen heritage deterioration.

Data on the interactions between earthen heritage and environmental processes, such as wind speed and sediment transport, were collected using methods including cup anemometers (Kristensen, 1998; Tan et al., 2016), smoke flares (Piscioneri et al., 2019) and sediment traps (Goossens and Offer, 2000; Nickling and Mckenna Neuman, 1997; Sherman et al., 2014). Further detail on the field experimental setups can be found in the method sections of the relevant papers.

A pilot field study was undertaken at Studland Beach, Dorset in July 2018 to test potential experimental setups for measuring environmental conditions (e.g. windspeeds and sediment transport along a transect). As all field equipment used at Suoyang was provided by the Dunhuang Academy, I tried, where possible, to source similar versions of the equipment from Oxford University. Several pieces of equipment were designed by the Dunhuang Academy, and were the only versions, meaning that I could not test them before the fieldwork period. For these pieces of equipment, the Dunhuang Academy was requested to test them before the fieldwork period.

3.4 Modelling

Findings from the field experiments were used to develop and validate a model that can investigate how the risk of earthen heritage deterioration varies under different environmental scenarios (Figure 3.8). To capture complex interactions over large spatial and temporal scales a cellular automaton (CA) model was chosen as an appropriate model type due to its computational efficiency and ability to resolve heterogeneous processes in a spatial specific manner.

CA models have been widely used within dryland research to investigate interactions of complex environmental processes. Models, such as the Discrete ECogeomorphic Aeolian Landscape model (DECAL) (Baas and Nield, 2007; Nield and Baas, 2008b), lattice gas cellular automaton model (LGCA) (Narteau et al., 2009) and the Vegetation and Sediment Transport model (ViSTA) (Mayaud et al., 2017a, 2017b), have been developed to simulate dune formation. Others, such as Bailey (2010), have used CA models capture the spatial patterning of vegetation in dryland environments. For the dune development models, the rate of dune formation is typically dependent on the modelled wind

velocity, sediment availability and rainfall. These processes are very similar to the processes that cause environmentally-driven deterioration of earthen heritage. As such, CA models already built to simulate dune formation could be adapted to investigate deterioration processes in an earthen heritage context.

As many earthen heritage sites, including Suoyang, are patchily vegetated, and as conservation strategies for these sites could include the use of vegetation, for example as windbreaks, capturing wind flow around vegetation elements is important. ViSTA was developed to assess the reactivation of dune fields in the Kalahari under future climates (Mayaud et al., 2017a, 2017b). Therefore, unlike DECAL and LGCA, ViSTA was built in a manner that captured the full range of feedbacks between vegetation, wind flow dynamics and sediment transport in dryland landscapes (Mayaud et al., 2017a, 2017b). Consequently, for research in this thesis, ViSTA was used as the base model. The Vegetation and Sediment Transport model for Heritage Deterioration (ViSTA-HD) was developed using field data from Suoyang (Chapter 6). ViSTA-HD spatially resolves the risk of earthen heritage deterioration under both current and potential future conditions. This allows the impact of future climate changes and conservation strategies on earthen heritage deterioration to be tested (Chapter 7).

Section 2

Environmental drivers of earthen heritage deterioration



Section 2: Overview

Section 2 addresses: objective 1 (assess the deteriorative impact of key individual environmental processes in the field); and objective 2 (assess the impacts of wind and rain on earthen heritage in the field), by assessing the impacts of wind and rain on earthen heritage in the field.

Chapter 4 (Paper 1) uses a controlled field experiment to assess individually the extent to which wind and rain events can cause deterioration. Chapter 5 (Paper 2) assesses the geomorphological signatures present on earthen walls at Suoyang to investigate how multiple, interacting environmental processes drive deterioration, and to compare the relative importance of wind and rain.

Given the interdisciplinary nature of this research, the papers presented in these chapters have been targeted at differing - but overlapping - audiences. Paper 1 is written for heritage scientists interested in earthen heritage while Paper 2 is targeted at geomorphologists who are either interested in weathering and erosional processes or interactions between natural and built systems.

4 A controlled field experiment to investigate the deterioration of earthen heritage by wind and rain (Paper 1)

Published as: Richards, J., Zhao, G., Zhang, H. and Viles, H. (2019) A controlled field experiment to investigate the deterioration of earthen heritage by wind and rain. *Heritage Science*. 7, 51. doi: <https://doi.org/10.1186/s40494-019-0293-7>.

Abstract

Earthen heritage constitutes 10% of sites on the World Heritage List and many of these sites are experiencing extensive deterioration caused by environmental forces, such as wind and rain. This study used a well-established test wall to investigate the impact of environmental conditions on the deterioration of earthen heritage at the remote and under-studied site of Suoyang Ancient City, Gansu Province, China, which is exhibiting widespread deterioration. Test walls have previously been used in earthen heritage research as they allow controlled experiments to be undertaken on complex, realistic structures without risking damage or loss of value to the historic material. This study used portable wind and rain erosion simulation devices to investigate experimentally (i) the comparative effect of wind, sediment-laden wind and wind-driven rain in causing deterioration to earthen heritage and (ii) how the incipient deterioration features produced by wind, sediment-laden wind and wind-driven rain on the test wall relate to the deterioration features recorded on the historic city walls. The test wall was subjected to low, medium and high intensities of clean wind, sediment-laden wind and wind-driven rain. The extent of deterioration produced was measured using repeat, high resolution laser scans before and after each test run. The deterioration features caused by each environmental force were notably different with clean wind removing the loose surface material, sediment laden wind causing pitting and wind-driven rain causing incipient gullyng. These incipient features compare well with more developed features seen on the historic walls. Wind-driven rain caused the greatest amount of deterioration while clean wind caused the least. However, as the frequency and duration of wind events at Suoyang is much greater than those of rain events, wind is likely to play an important role in the deterioration of earthen heritage over annual timescales. These findings show that conservation strategies at rammed earth sites like Suoyang need to address the impact of multiple environmental forces, such as clean wind, sediment laden wind and wind-driven rain.

Key words: Earthen heritage, deterioration, field experiment, northwest China

4.1 Introduction

Earthen heritage sites make up 10% of the World Heritage List with many of these sites located in arid and semi-arid environments (WHEAP, 2012). Despite the universal value of earthen heritage, many sites have, and are continuing to experience, extensive deterioration which threatens to reduce their value (Oliver et al., 2000; Pu et al., 2016a; Shao et al., 2013).

Earthen heritage can be constructed using a variety of methods including rammed earth, adobe, wattle and daub and cob (Velde, 2008), each of which has its own complex set of material properties (Rainer, 2008). This paper will focus on the deterioration of rammed earth as the sites comprising this material have been less investigated compared to adobe (e.g. Brown et al., 1979; Guerrero, 2002; Illampas et al., 2013; Oliver et al., 2000; Selwitz et al., 1990; Taylor, 1990), despite rammed earth experiencing extensive and widespread deterioration (Du et al., 2017; Shao et al., 2013). Hereafter, earthen heritage will refer to rammed earth in arid to semi-arid environments unless otherwise stated.

Deterioration of earthen heritage is affected both by material properties and environmental conditions (Rainer, 2008). Variations in material properties across a site (e.g. compressive strength and grain size) can help identify areas which may be particularly at risk of future deterioration (Du et al., 2017). However, to limit the extent to which historic material is altered, conservation strategies need to understand how environmental conditions cause deterioration (Richards et al., 2018).

Previous studies have highlighted the importance of rain, wind and sediment-laden wind as drivers of earthen heritage deterioration, with rain noted as causing the greatest rate

of deterioration over short periods of time (Bui et al., 2009; Crosby, 1983; Fodde and Khan, 2013; Rainer, 2008). Commonly a combination of processes cause deterioration (Brown et al., 1990; Rainer, 2008). Studies have tended to be undertaken either in laboratory experiments where small samples are exposed to controlled environmental conditions (Mao et al., 2015, 2008; X. D. Wang et al., 2010), or in the field where test or historic walls are exposed to natural conditions and monitored after a period of time (Bui et al., 2009; Lombillo et al., 2014; Selwitz et al., 1990). In the laboratory, the use of small samples has meant that deterioration has often been measured by weight loss. Some deterioration features, such as scouring and flaking, have been produced under laboratory conditions (Cui et al., 2019), but the scale of the deterioration feature is limited by the size of the sample. For example, on a 7 x 7 x 7 cm cube, flakes larger than 7 cm wide cannot form, and the formation of larger deterioration features (e.g. slumping) are unlikely to be captured.

In the field, studies have tended to use features of deterioration visible on the walls to infer back to the processes which caused the deterioration (Du et al., 2017). However, as the environmental history of the site since construction tends to be unknown, uncertainty is raised by issues of equifinality, where two different process histories may have caused the same deterioration feature to occur (Haines-Young and Petch, 1983). Furthermore, field studies have tended to be concentrated on a small number of accessible and well-studied sites (e.g. Çatalhöyük, Turkey) (Campiani et al., 2019; Lercari, 2019; Matero and Moss, 2004) with many other, more remote sites not being studied limiting the wider applicability of findings.

To design successful conservation strategies (i.e. strategies which reduce the rate of earthen heritage deterioration), a greater understanding of the impact of environmental conditions on a wide range of earthen heritage sites is needed. This study utilised a unique opportunity for researchers to investigate the impact of environmental conditions on the deterioration of earthen heritage at the remote, and under-studied site of Suoyang Ancient City. The site is located on the ancient Silk Road in Gansu Province, northwest China over 900km from Lanzhou, the Province capital, and over 150km from the town of Dunhuang. The site is now exhibiting widespread deterioration, and the site managers are eager to prevent further loss of valuable ancient earthen architecture. This study uses a field experiment on a test wall in combination with surveys of deterioration features on ancient walls to investigate i) the comparative effect of wind, sediment-laden wind and rain in causing deterioration to earthen heritage and ii) how the incipient deterioration features produced by wind, sediment-laden wind and wind-driven rain on the test wall related to the deterioration features recorded on the historic city walls.

4.2 Methods

4.2.1 Site description

Suoyang Ancient City (锁阳城), hereafter known as Suoyang, is an archaeological site located on the ancient Silk Road in remote, semi-arid northwest China. It was built from rammed earth in the Han (206 BC–220 AD) and Tang (618 – 907 AD) dynasties and consists of inner and outer city walls, a monastery, stables, archery platforms and extensive irrigation channels (Figure 4.1). It was enlisted as part of the Silk Roads World

Heritage Site in 2014 as an exceptional example of a communication and frontier defence settlement along the eastern part of the Silk Roads.

The site was abandoned ~400 years ago due to a decline in overland trade and the avulsion of the nearby river away from the city. The remains of the city walls now exhibit a variety of deterioration features caused by the interaction of wind, sediment transport and rain with the earthen walls, including flaking, undercutting, polishing and scouring as well as the formation of gullies, cracks, fractures, slumps and collapses (see Figure 4.1 for examples). In addition, numerous cavities are present across the wall face. These features are associated with the construction of the walls, indicating the location of timber supports (Maniatidis and Walker, 2003; Jaquin, 2012). Some cavities have since been inhabited by creatures and may provide points of weakness for ongoing deterioration. Further research is needed at Suoyang to assess the importance of these in the deterioration process as their location and micro-climate could influence deterioration patterns.

Research by the Dunhuang Academy (unpublished) found the thickness of the rammed earth layers at Suoyang varies between 8 – 24 cm and the natural density of the walls ranges between 1.55 and 1.77 g cm⁻³. The grain size distribution of the historic earthen material is polymodal with peaks in grain size <75 µm and between 100 – 250 µm and is positively skewed. Additional material (such as red willows) were found in the walls but only in localised areas.

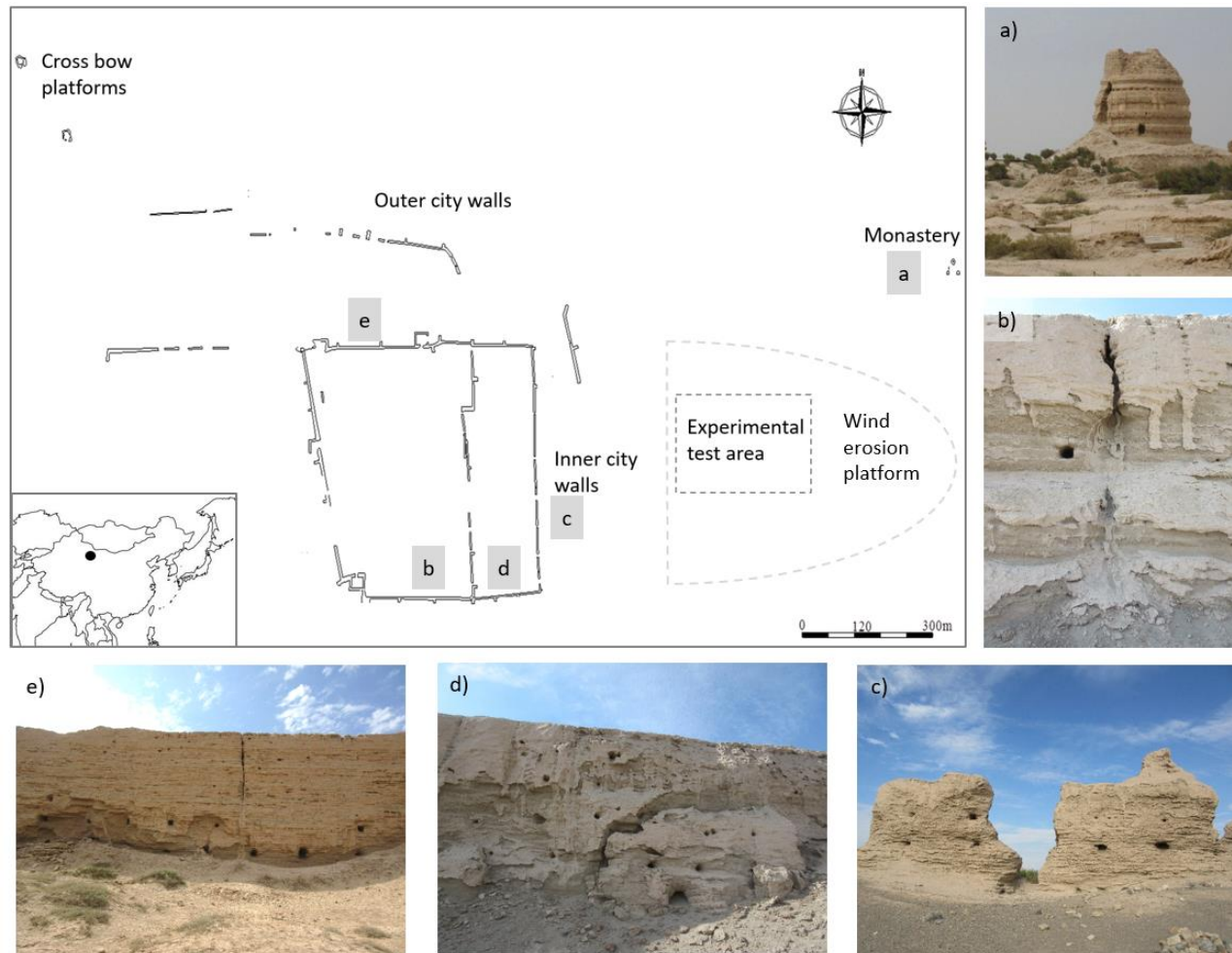


Figure 4.1: A site map of Suoyang showing the location of the inner and outer city walls, cross bow platforms, monastery, wind erosion platform and experimental test area. Inset is the location of Suoyang within China. Photos show a) the Buddhist monastery, b) a gully, c) part of the east inner city wall that has deteriorated into distinct sections, d) the detachment of a section of the southern inner city wall and e) a crack in the southern inner city wall. The location of photos a) – e) at Suoyang are indicated in grey boxes on the site map.

The site is a challenging setting for research due to its remoteness, its exposure to an extreme continental climate and lack of environmental and historical data from the site. However, since 2015, an experimental area has been established to the east of the main site, comprising several test walls, which allows experimental research into the impact of the environment and conservation strategies on earthen heritage to be undertaken.

4.2.2 Environmental conditions

According to the Dunhuang Academy, rainfall at Suoyang can vary between 30 and 75 mm with the majority of rainfall occurring between March and September and little rainfall in the winter months. The prevailing easterly wind is strongest in the summer months with westerlies also occurring September to November. For an overview of regional climate and recent changes in climate in northwest China see Sun *et al.* (2013).

In the absence of long-term climatic data at Suoyang, wind and rain measurements were taken at the site using an automatic weather station in the six months preceding and four months proceeding this experiment (March to December 2018). Additional wind measurements were recorded at Suoyang between August 2015 and July 2016 following the building of the test walls at the site.

To measure sediment transport at Suoyang, a wedge shape sediment trap orientated to the prevailing wind and circular sediment trap were deployed between June and September 2018 in an open area also located to the east of the main site. The mass of sediment captured was analysed once a month.

4.2.3 Experimental design

To investigate the comparative effect of wind, sediment-laden wind and rain in causing deterioration to earthen heritage, this study was undertaken on a small test wall located

in the experimental test area. Test walls have previously been used in earthen heritage research (e.g. at Fort Selden) (Oliver et al., 2000; Selwitz, 1995; Taylor, 1990) as they allow experiments to be undertaken under field conditions on complex, realistic structures without risking damage or loss of value to the historic material. Experiments on test walls in the field have advantages over laboratory experiments on large specimens, as test walls are exposed to, and can equilibrate with, complex natural conditions such as fluctuating ground water and changes in internal moisture and salt content which can cause material loss (Lercari, 2019), but cannot be realistically simulated in the laboratory. Field experiments also have advantages over monitoring the impact of environmental conditions on test walls and historic earthen remains, as they are quicker and more easily controlled. Finally, field experiments on test walls are preferable to field experiments on historic earthen walls which could cause unwanted accelerated deterioration.

The test wall was built in April 2015 by scientists from Dunhuang Academy, specifically to replicate the material properties of the historic walls at Suoyang. It was built from loessic soils taken from Suoyang's wind erosion platform, which had a similar particle size distribution to that of the historic material, and had no additives to best represent Suoyang's material composition. The wall was constructed using traditional ramming techniques by building wooden forms the size of the wall, in which a layer of soil was added and rammed down using a hammer. This process was repeated six times forming a wall measuring 64 cm high and 76 cm wide, with a density of 1.70 g cm^{-3} . The test wall is thus directly comparable in materials, construction and density to the least deteriorated ancient walls at Suoyang. The wall was then left exposed for three years and is now assumed to be in equilibrium with environmental conditions.

The deterioration of the wall surface before this study was undertaken was negligible except for a few small areas at the edge of the wall which exhibited some incipient polishing and scouring features. It should be noted that these test walls are not exact replicas of the real site walls, being orders of magnitude younger than the historic site and thus environmental forces may interact differently with the test walls compared to the historic walls. Consequently, all findings on the test walls have been compared with the formation of deterioration features on the historic walls. This was achieved by visually assessing shape and size of the deterioration features on the historic walls and comparing them to the features on the test walls. As the deterioration features visible on the historic wall are the result of multiple interactions between the site and environmental drivers over time, the features have to be interpreted as part of a signature of deterioration. This is explained in more detail in Figure 5.3.

An on-site field deterioration experiment was undertaken on the test wall in August 2018 as part of a wider project investigating potential future conservation methods for Suoyang. Field-based deterioration tests have previously been used in earthen heritage (Peng et al., 2015; Shao et al., 2013) and desert environmental studies (Belnap et al., 2007; Belnap and Gillette, 1998, 1997; Eldridge and Leys, 2003; Li et al., 2004) to quantify erosion rates, but have not been used to compare the effectiveness of different environmental forces, nor to compare the incipient deterioration features produced (e.g. gullies) with deterioration features seen on the historic walls. The extent of deterioration is affected by both the erodibility of the test wall (i.e. the cohesiveness of the earthen material) and the erosivity of environmental forces acting on the wall (i.e. the ability of a process to cause erosion). As the erodibility of the test wall is assumed to be constant across all test runs, this experiment compares the difference in erosivity

between three environmental forces (wind, sediment-laden wind and wind-driven rain) on earthen heritage.

4.2.4 Test wall preparation

The top surface (~0.5 cm) of the front face of the test wall was initially removed with a chisel, exposing fresh material. The surface was then brushed down using a soft brush to remove any loose material. As the building of the test wall was highly controlled and is assumed to be in equilibrium with the surrounding environment, the material properties of the wall are considered as homogeneous throughout the wall. For each test run, the surface was lightly chiselled again and then brushed to prevent any cumulative impacts of previous test runs on the surface of the wall. Figure 4.2a – c shows the surface topography of the test wall after the initial surface preparation and before the first experimental run. This topography was indicative of the surface roughness before each test run.

For erosion studies in desert environments, similar methods of artificially preparing a surface have commonly been used to ensure comparability between test runs (Belnap et al., 2007; Belnap and Gillette, 1998, 1997; Eldridge and Leys, 2003; Li et al., 2004).

However, it should be noted that by exposing fresh material for each test run, the erodibility of the test wall face is likely to be similar to newly exposed areas on the historic wall (e.g. material exposed after processes of flaking, cracking and collapses) and it is likely to be higher in comparison to areas of the historic walls which have weathering features such as crusts present.

The test wall was divided into three 20 cm x 20 cm test areas using six screws as reference points (Figure 4.2). The size and location of test areas at the top of the wall

were constrained by the diameter of the funnel on the portable wind tunnel and also by restrictions in lowering the device.

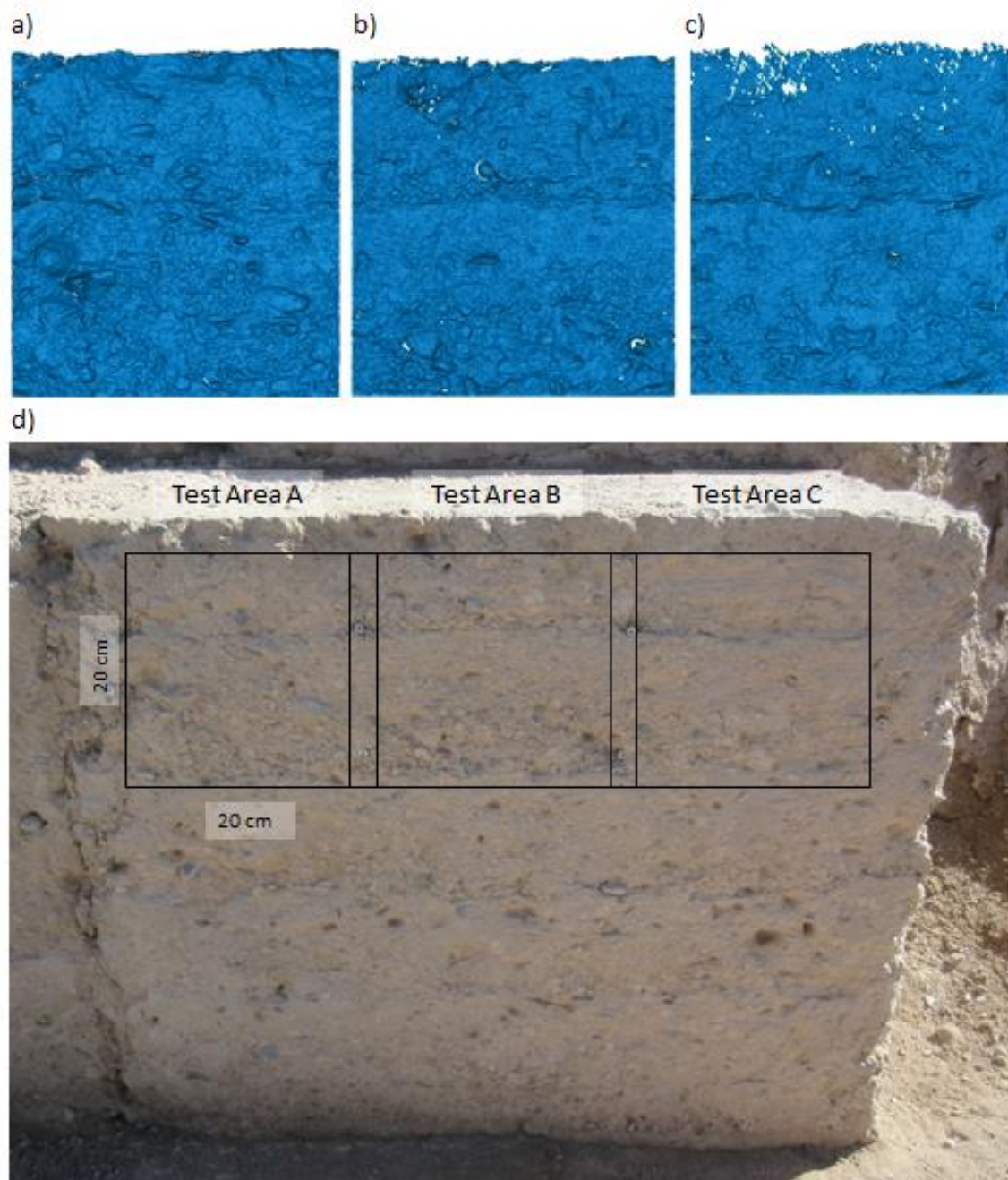


Figure 4.2: Texture maps showing the surface topography after initial surface preparation and before the first set of experimental runs of a) test area A, b) test area B, c) test area C and d) the location of the test area on the test wall at Suoyang. Light blue indicates raised areas and dark blue indicates lower areas. Maps in panels a) to c) were produced at the Dunhuang Academy using the software licensed for use only in China.

Laser scanning has previously been used to monitor erosion rates at earthen heritage sites over millimetre scales (Barnard et al., 2016; Barton, 2009; Lercari, 2019) but sub-millimetre, highly detailed repeat laser scanning assessing the impact of environmental processes on earthen heritage deterioration has not been attempted. For this study, before each test run, the test area was laser scanned with a handheld Creaform Handy SCAN 700 3D™ laser scanner (0.2mm accuracy, 0.050 mm resolution) using the screws as reference points. In addition, 19 black and white circular targets were used during scanning to improve the accuracy of the laser scanning data. To ensure the accuracy of the laser scanner, two scans of the same area of test wall were compared and the error between the two scans was found to be less than 0.2 mm. The specific error for each scan was not captured, as such results showing a change in surface area of less of than 0.2 mm should not be viewed as significant and these areas are coloured green in the results. After each test run, the test area was re-scanned using the same process.

4.2.5 Deterioration test

The test wall was subjected to wind, sediment-laden wind and rain, each at 3 different intensities, resulting in a total of nine test runs (Table 4.1). The total number of test runs undertaken on the test wall were limited due to each test run requiring the surface of the test wall to be removed. The intensities used in the tests were based on findings in the literature (e.g. Mao et al., 2015, 2008; X. D. Wang et al., 2010) and recorded conditions experienced at Suoyang to simulate a low, medium and high intensity event. Each experimental run focused on a single test area and the other test areas were covered to prevent deterioration occurring.

Table 4.1: Conditions used in the deterioration test

Run	Process	Condition	Test Area	Rational for condition
1	Clean wind for 5 mins at:	12 m s ⁻¹	A	Threshold in wind tunnel studies (X. D. Wang et al., 2010)
2		17 m s ⁻¹	B	Maximum wind speed in storm at Suoyang (14 th -15 th Aug 2018)
3		25 m s ⁻¹	C	Highest wind speed recorded in 2015-16
4	Sediment-laden wind 80 g min ⁻¹ for 5 mins at:	12 m s ⁻¹	A	Threshold in wind tunnel studies (X. D. Wang et al., 2010)
5		15 m s ⁻¹	C	Intermediate wind speed as 17 m s ⁻¹ caused visible damage
6		17 m s ⁻¹	B	Maximum wind speed in storm at Suoyang (14 th -15 th Aug 2018)
7	Rainfall at 0.2 L min ⁻¹ for:	20 secs	C	The time at which visible deterioration occurred
8		1 min	B	Volume of water is equivalent to the 2 nd highest maximum daily rainfall in 2018 at Suoyang
9		2 mins	A	Volume of water is equivalent to the maximum daily rainfall in 2018 at Suoyang

All equipment used in the deterioration tests is patented by the Dunhuang Academy and was specifically developed to undertake field research on earthen heritage deterioration. The equipment was designed to i) provide greater control over the erosivity of rain and wind than that used in previous research on earthen heritage, such as fans to generate wind (X. D. Wang et al., 2010) and ii) be easily portable for use at remote, exposed sites. All equipment used had been calibrated by the manufacturer in a laboratory environment. Given the manufacturer's calibration and the limited total number of runs that could be undertaken on the test walls, all equipment was calibrated in-field away from the test wall, to ensure that the net impact of the environmental condition was achieved (e.g. the velocity of wind speed produced, the total amount of sediment entrained in the wind per minute and the total amount of water sprayed per minute).

The portable wind erosion simulation device (PWESD) is formed of a generator, fan, sediment funnel and a wind tunnel which is 92 cm long and 12 cm wide (Figure 4.3a). For each test run, the mouth of the wind tunnel was placed 20 cm away from the test wall with the wind tunnel perpendicular to the wall to ensure that the test area was evenly subjected the wind generated from the PWESD, while minimising the effect from any cross winds that may have occurred during the experiment. At this distance away from the wall, the wind speed was assumed to be constant across the test area. The PWESD was run for 5 minutes, as in Wang et al. (2011), to generate clean winds at 12, 17 and 25 ms⁻¹.

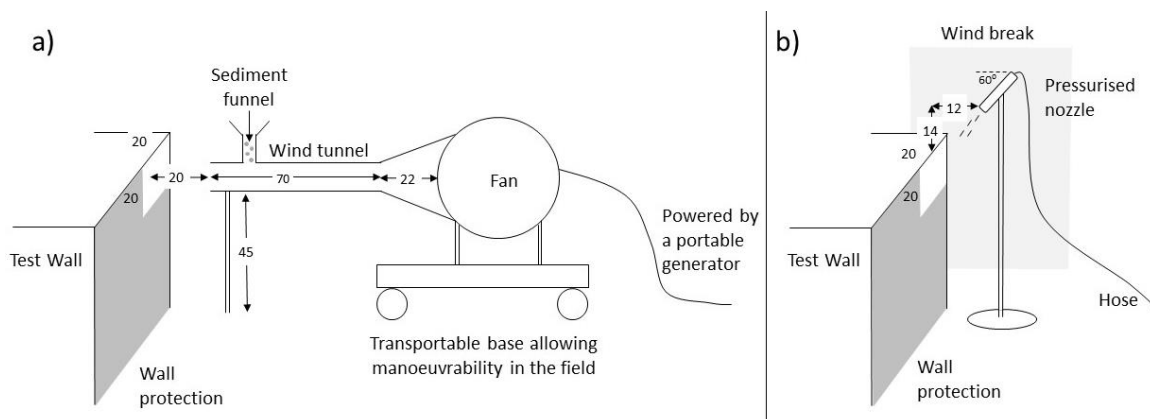


Figure 4.3: The test setup of a) the Portable Wind Erosion Simulation Device and b) the Portable Rain Erosion Simulation Device in front of Test Area C on the test wall. All measurements are in centimetres.

The PWESD was also used for the sediment-laden wind tests. The PWESD was set up as for the clean wind tests except for the addition of sediment which was continuously fed through the sediment funnel throughout each test run (Figure 4.3a). The sediment used was taken from the surrounding dune deposits and sieved to remove sand particles and organic matter greater than 2 mm to represent sediment entrained at the site where grain size analysis showed all particles were less than 2 mm. Subsequent particle size analysis showed that the sediment used in the deterioration test was comparable to the normally entrained material, with a polymodal distribution with peaks at 19 μm , 136 μm

and 1227 μm and was positively skewed. The wall was subjected to wind speeds of 12, 15 and 17 ms^{-1} for 5 minutes with sediment being entrained in the wind at a rate of 80 g min^{-1} for each test run. A lower maximum wind speed was used for sediment-laden wind, compared to the clean wind test, as the 17 ms^{-1} wind caused significant visible damage to the test wall. The majority of the sediment was entrained by the wind in the upper half of the wind tunnel causing the upper half of the test area to be subjected to a greater quantity of sediment than the lower half.

The wind-driven rain was created using a Portable Rain Erosion Simulation Device (PRES D) (Figure 4.3b). The device was set up at a 60° angle to the test wall to mimic driving rain, with the nozzle 12 cm away from the wall face. A windbreak was used to prevent cross winds affecting the test area. The device was run using water brought to the site at 0.2 L min^{-1} (the lowest volume possible) for 20 seconds (1.9 mm cm^{-1}), 1 minute (4.6 mm cm^{-1}) and 2 minutes (8.3 mm cm^{-1}).

The PRES D was designed to provide an even coverage of water to the test area.

However, due to the low pressure used, the rainfall was focused in the centre of the test area and the spatial area of rainfall impact increased over time resulting in the amount of rainfall per cm^{-1} not being directly proportional to the duration of the test run. Given the remote location of the site, it was not possible to fix the water distribution produced by the simulation device under low pressure – and ideally a lower pressure than the one used in the experiment would have been used to mimic local rainfall intensity. However, despite these limitations, the intensity of the rainfall simulated in this experiment is likely to be representative of heavy rainstorm events. To investigate the impacts of lighter rain events, misting devices could be used in the field, or large-scale laboratories

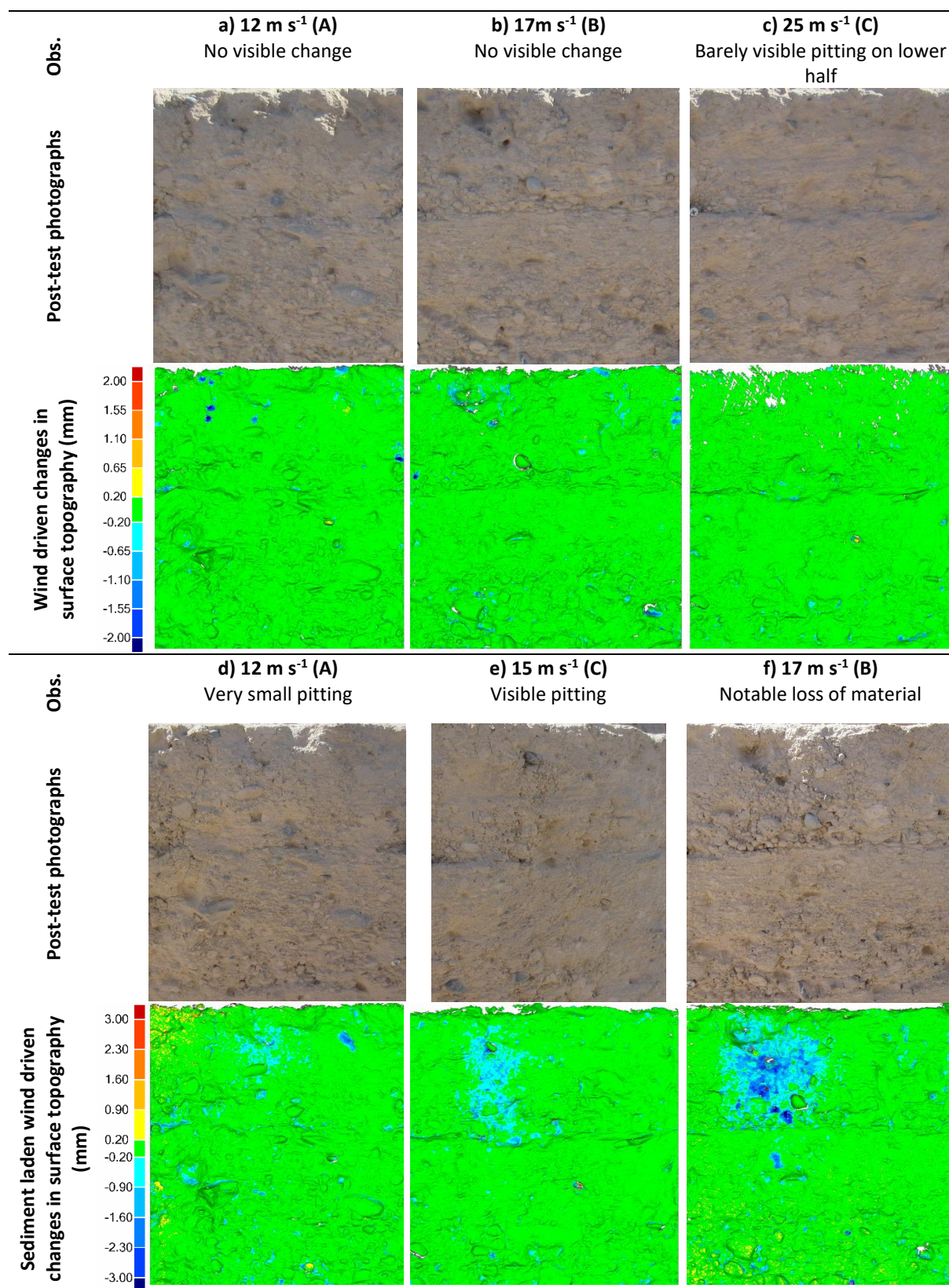
such as the newly opened Multi-coupling field Laboratory at the Dunhuang Academy could be used.

4.2.6 Data analysis

The laser scanning surface spatial grid data was analysed using the software, Geomagic Control. Each point cloud was processed into a 3D mesh. Pre and post-test meshes were aligned manually and then adjusted by the software using the reference screws placed in the wall. The topography of the meshes was then compared to identify any changes to the surface of the wall ± 0.2 mm. The differences between the two scans were mapped allowing the spatial patterns of erosion to be compared between test runs.

4.3 Results

When the wall was subjected to clean wind, the majority of the surface showed no significant change (Figure 4.4). During the 12 and 17 m s⁻¹ tests, we observed no visible changes to the wall surface but the deviation maps showed that loose particles were removed off the wall surface in small localised areas (see the blue areas in Figure 4.4a, b). This deflation of material on the wall tended to be from raised areas (Figure 4.2a-c) resulting in a smoother surface forming. When the wall was subjected to 25 m s⁻¹ wind, erosion occurred on some raised surfaces and also within hollowed areas of the test wall resulting in some visible pitting (Figure 4.4c). However, despite the presence of pitting, the total spatial extent of deterioration did not increase (Table 4.2). The maximum depth of erosion increased with increasing wind speed but the impact was highly localised with less than 1% of the surface area being significantly deteriorated on all clean wind tests (Table 4.2).



Continued over page

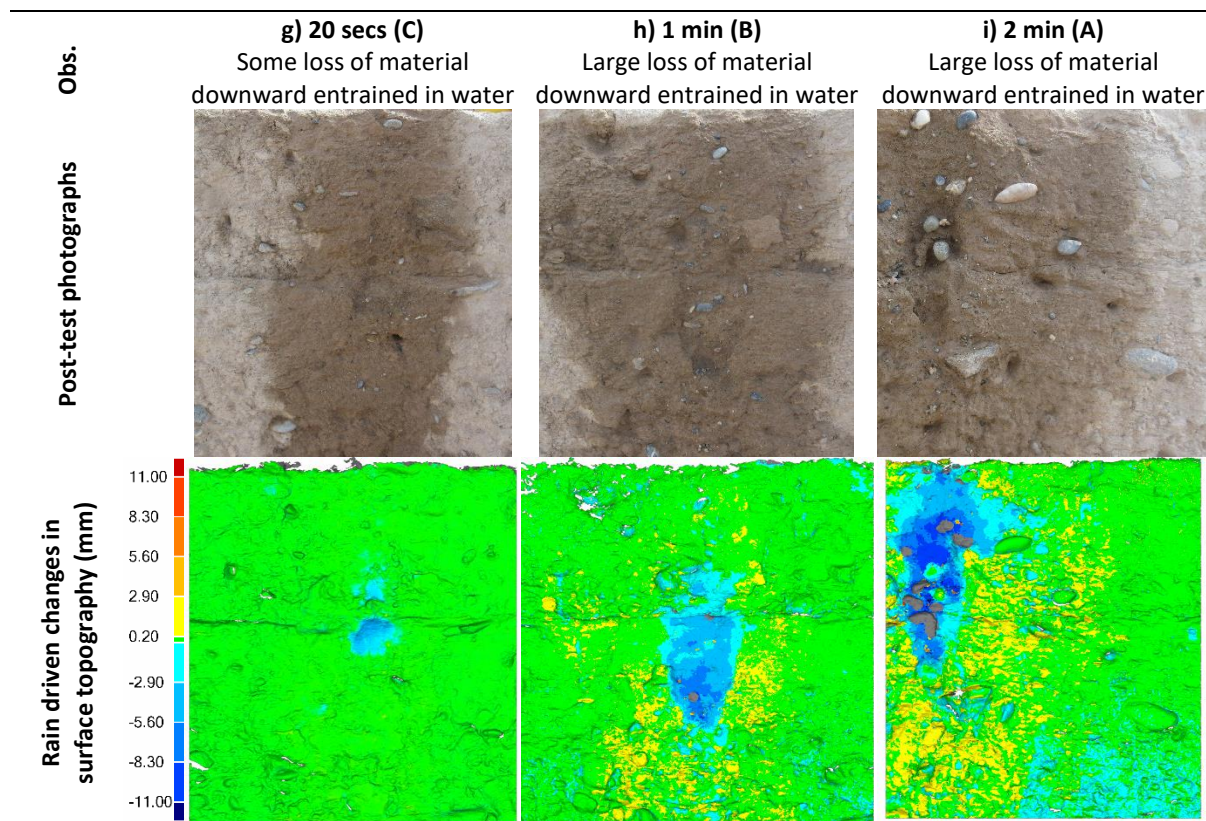


Figure 4.4: Deterioration caused by a -c) wind, d-f) sediment-laden wind and g-i) rain with i) visual observations (Obs.) while the deterioration test was undertaken, ii) post-test photographs of the test area and iii) the laser scanning deviation map showing changes in surface topography (blue = negative surface change, green = no significant change and yellow = positive surface change), note the difference in the quantitative scale between rows (mm). The letter (A), (B) or (C) refers to the test area the experiment was undertaken on.

Table 4.2: The maximum depth and spatial extent of erosion after deterioration tests.

Condition applied to test area		Maximum depth of erosion (mm)	Area of spatial erosion in mm ² and as a percentage of total area
			(blue areas in Figure 4.4)
Clean wind for 5 min at the speed of (m s ⁻¹):	12	6.49	228 (0.6 %)
	17	7.90	316 (0.8 %)
	25	10.69	292 (0.7 %)
Laden sediment wind 80 g min ⁻¹ for 5 min at the speed of (m s ⁻¹):	12	4.29	1132 (2.8 %)
	15	11.00	1804 (4.5 %)
	17	11.00	3576 (8.9 %)
Rainfall at 0.2 (L min ⁻¹) for (s):	20	9.24	768 (1.9 %)
	60	10.62	3956 (9.8 %)
	120	11.20	7276 (18.2 %)

When the test areas were subjected to sediment-laden wind there was notably more deterioration compared to the clean wind experimental runs (Figure 4.4d–f). This deterioration was concentrated on the upper half of the test areas in association with the design of the PWESD. However, on all sediment-laden wind tests visible pitting occurred and, in contrast to when the test walls were exposed to clean wind at the same speeds, the deterioration was not limited to raised areas. For the sediment-laden wind tests, the spatial area of impact and the maximum depth of erosion increased with wind speed, with a notable loss of material occurring at 17 m s^{-1} (Table 4.2). On the lower half of the test areas there were localised areas of deterioration with spatial patterning similar to the patterning on the test areas exposed to 25 m s^{-1} clean wind, i.e. localised removal of material on both the raised areas and in some hollows.

Wind-driven rain caused significant deterioration with the water visibly entraining the material and transporting it down the wall face (Figure 4.4g-i). Once a small hollow was formed, the water was channelled into this area causing further material to be entrained. Significant deterioration could be seen after 20 seconds and the formation of an incipient gully could be seen after 1 minute (Figure 4.4g, h). After 2 minutes, the flow of water down the wall caused the greatest amount of erosion (Table 4.2) and also further deterioration to the lower sections of the wall (Figure 4.4i). Below the incipient gullies, there were some areas which increased in height (shown in yellow in Figure 4.4h, i). This could have been caused by the wall swelling as it became saturated by water or by material that was entrained further up the wall being redeposited on the lower sections of the test area.

4.4 Discussion

These findings support previous studies which have found that the extent of deterioration is affected by the environmental conditions earthen heritage is exposed to, with clean wind causing the least and rain causing the greatest volume of deterioration (Bruno et al., 1968; Clifton, 1977; Mao et al., 2015; Shao et al., 2013; X. D. Wang et al., 2010). However, in contrast to previous studies, the methodology used in this study also resulted in the formation of incipient deterioration features under controlled environmental conditions. More developed versions of these incipient deterioration features are seen on the historic walls at Suoyang (Figure 4.5). This suggests that this field based experimental method provides i) a more realistic deterioration mechanism than using small samples in the laboratory, whilst ii) still being able to control and measure the impact of individual environmental conditions on earthen heritage deterioration, minimising the risks of equifinality that can arise when two different processes may have caused the same deterioration feature to occur.

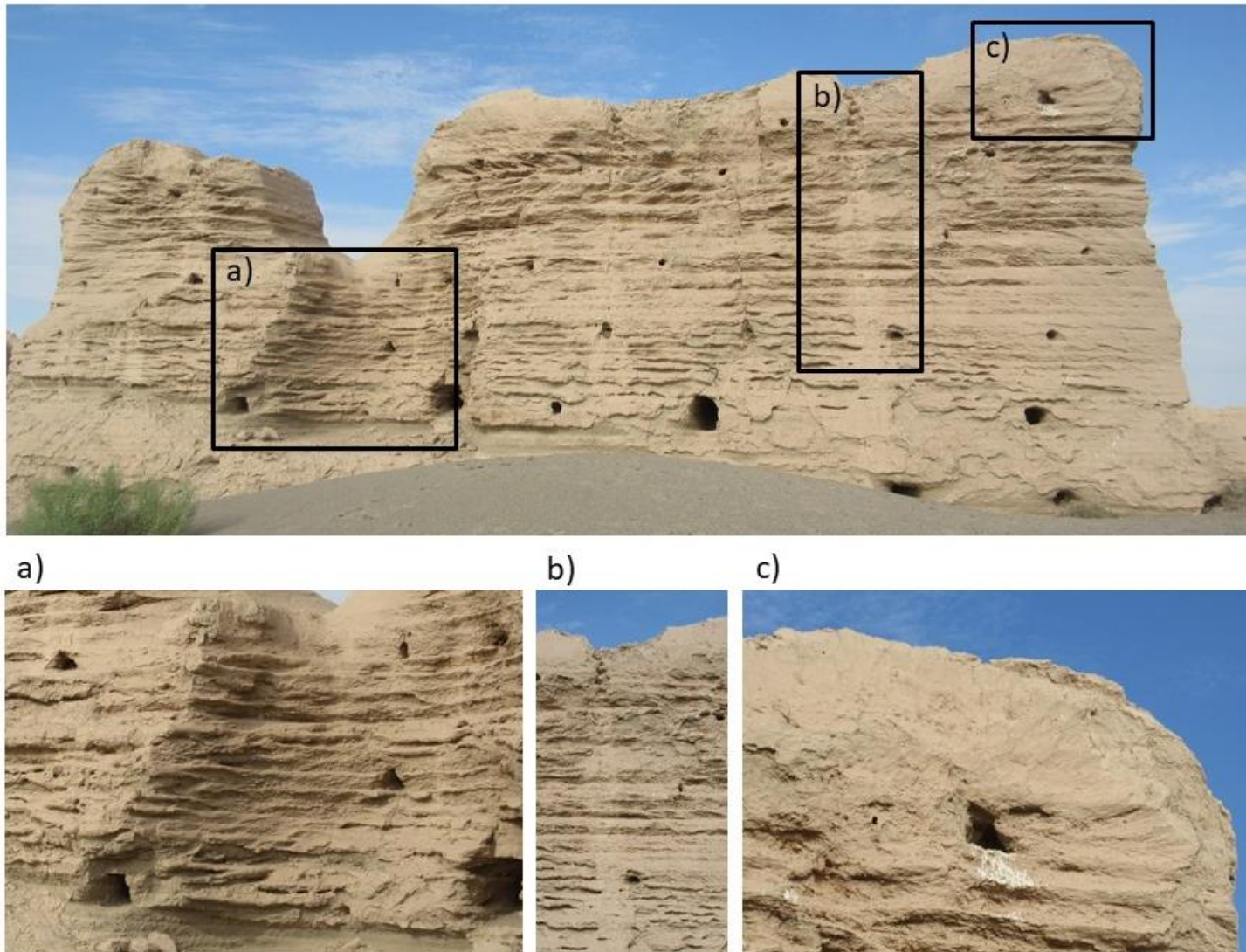


Figure 4.5: Examples of deterioration features at Suoyang: a) pitting, b) an incipient gully (see Figure 4.1b for a developed gully) and c) wind polishing.

For clean wind, previous lab studies identified 12 m s^{-1} as a threshold for deterioration to occur (X. D. Wang et al., 2010). High accuracy laser scanning in this study showed that deterioration was already occurring on protruding areas at this wind speed resulting in a smoother surface. This decay process was invisible to the naked eye and given the small quantity of sediment eroded, standard methods which capture eroded sediment would have been unlikely to accurately record the eroded material. This suggests that deterioration processes may be occurring at lower speeds than previously thought and that laser scanning could further be used to detect wind driven erosion before it becomes visible. On the historic walls at Suoyang, areas above the saltation layer (40 cm above the ground, Appendix C, Figure C.6) exhibited features such as polishing on wall tops and rounding of corners (Figure 4.5). Interestingly, at 25 m s^{-1} the deterioration caused by clean wind also caused incipient pitting in some concave areas. This suggests that there is likely to be a threshold between 17 and 25 m s^{-1} where clean wind goes from only being able to remove already loose grains of protruding earthen sediment to being able to dislodge more firmly cemented grains (Mao et al., 2015).

Sediment-laden wind caused notably more deterioration than clean wind. Whilst the uneven distribution of sediment across the test area was not intended, it showed that the concentration of sediment in the wind influences the type of deterioration features that are formed, with winds with high concentrations of sediment causing pitting while low concentrations of sediment form polishing features similar to those produced by clean wind (Figure 4.4). The highly concentrated sediment laden wind in the upper half of the test area could be representative of deterioration processes occurring in sand storm events or in areas where sediment transportation is high, such as at the side of a gap between walls or at the top of a dune that abuts to an earthen wall (Figure 4.5). In

these areas, pitting features are likely to have formed due to the impact of the kinetic energy of the sand on the earthen material causing particles to be loosened and thus susceptible to being entrained and removed by the wind (Mao et al., 2015). The areas subjected to the less highly concentrated sediment-laden wind could represent areas of wall which have depositional elements upwind such as vegetation, minimising the extent of transported sediment that impacts against the wall (Wolfe and Nickling, 1993).

Furthermore, the small pitting that occurred on the test area when it was subjected to 12 m s^{-1} sediment-laden wind, suggests that the presence of sediment in the wind can significantly increase the amount of deterioration compared to non-sediment laden winds occurring at the same speeds. In addition, the extent of pitting increased with increasing wind speed - in a non-linear fashion for the maximum depth of pitting and in an approximately linear fashion for the area of pitting on the wall surface (Table 4.2). For low wind speeds, the wind is less likely to be able to fully entrain and transport sediment and any transported sediment which does interact with the historic site will have a low erosivity. Thus, deterioration by lower speed sediment-laden winds is likely to be limited spatially to sections of walls within or just above the saltation zone (Kok et al., 2012; Williams, 1964), with for example, scouring or pitting at the base of walls. High wind speeds are more likely to be able to transport airborne sediment with higher kinetic energy resulting in the wind having a greater erosivity. Consequently, in addition to causing pitting within the saltation zone, faster sediment-laden winds are more likely to cause pitting on higher areas of earthen sites and also cause a faster rate of pitting (Mao et al., 2015, 2008; X. D. Wang et al., 2010).

Wind-driven rain caused significant deterioration by weakening the cemented material between soil particles and transporting material down the face of the wall (Shao et al., 2013). The uneven distribution of rain resulted in deterioration being focused around the centre of the spraying area. This meant that initially the central section of the test area was subjected to a high volume of water ($> 4 \text{ mm min}^{-1}$). This may not be representative of rainfall events that commonly occur at Suoyang, which tend to occur over several hours and produce to up 4 mm of rainfall. However, according to the Dunhuang Academy, as up to 30 mm of rainfall has occurred in a single rainfall event at Suoyang, the high volume of water used in the deterioration test could be more reflective of these extreme, high intensity rainfall events. Once an incipient gully started to form, water from other areas of the wall face was also channelled into this gully starting a positive feedback loop that has been observed on gullies at Suoyang during rain events. Additional feedbacks were observed on the test areas, such as the expansion of the wetted material and the deposition of entrained material lower down on the wall face (Figure 4.4h, i), which are also found at the historic site (Figure 4.5b). Therefore, this suggests that if the surface of a wall at Suoyang is primed with a small fissure, weakness or pre-existing channel, incipient gullies could form after a single high intensity rainfall event, highlighting the high erosivity of rain on earthen heritage that has previously been acknowledged (e.g. Bui et al., 2009; Crosby, 1983; Fodde and Khan, 2013).

However, whilst rain may have caused the greatest amount of erosion to the test wall, the sporadic nature of rain events at Suoyang is likely to limit its impact on deterioration over longer temporal periods (Figure 4.6). At Suoyang, rain events only occur several times a year and commonly only produce several millimetres of rain over several hours.

In contrast, winds of 12 m s^{-1} or faster occurred for a total of 720 h (30 days) between August 2015 and July 2016. This suggests that over an annual period, incipient gullies are likely to form during rain events in areas which have a pre-conditioned fissure or weakness but due to the more frequent nature of wind events, more developed wind polishing features are likely to form on exposed areas of the site. Furthermore, even though winds of 25 m s^{-1} are rare at Suoyang in the open field, only recorded once between August 2015 and July 2016, in gaps between wall sections at Suoyang, the air flow is compressed resulting in wind speeds potentially increasing by 33 % (unpublished data from Suoyang). Therefore, parts of the historic walls around these 'wind tunnel' areas are regularly subjected to significantly higher wind speeds than recorded generally for the site. Sediment laden wind in these areas are likely to significantly contribute to scouring and hollowing within the saltation zone and as extensive hollowing also occurs in these 'wind tunnel' areas above the height of saltation, this suggests that here too, clean wind can cause pitting and hollowing (Figure 4.6).

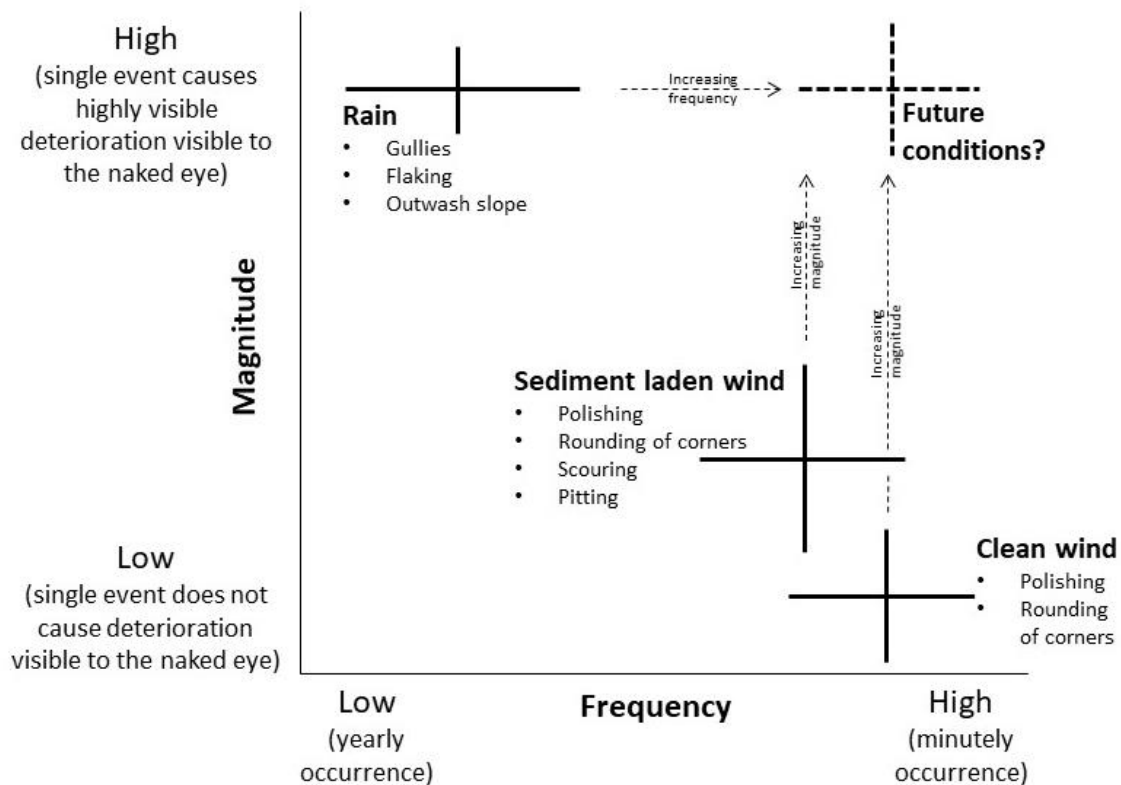


Figure 4.6: A conceptual diagram showing the frequency and magnitude of environmental conditions and their associated features on earthen heritage deterioration at Suoyang. The solid crosses show the range of frequencies and magnitudes over which clean wind, sediment laden wind and rain currently operate. The potential impact of future environmental conditions is shown with a dashed cross.

This study shows that earthen heritage deterioration at Suoyang is currently driven by multiple processes which operate over different frequencies and magnitudes and produce notably different deterioration features. However, in north west China the magnitude and frequency of wind and rain events have varied over decadal to centurial timescales (Deng et al., 2017; Yang et al., 2011; Zhang et al., 2008). Future climate projections are uncertain but wind speeds and annual rainfall are generally predicted to increase in northwest China (Guo et al., 2017; Jiang et al., 2010; Shi et al., 2007; R. Wang et al., 2019), suggesting that rates of deterioration at sites such as Suoyang are likely to also increase. Figure 4.6 conceptually shows the current frequency and magnitude of clean wind, sediment laden wind and driving rain events at Suoyang, but could also be applied to other earthen heritage sites in semi-arid areas. The current frequency and

magnitude of events is based on the limited environmental data collected at Suoyang between 2015 and 2018, and also informed by expert opinion from site managers who have a deep understanding of the local climate.

Figure 4.6 also highlights that the frequency and magnitude of environmental events are not static and suggests how they could be influenced by future projected changes in climate. Increasing i) the frequency of rain storm events, or ii) the magnitude of either wind speed events or the amount of sediment transported by the wind, would increase the potential erosivity of wind and wind-driven rain, thus increasing the amount of deterioration experienced at Suoyang. For future conservation to be successful, these potential changes in the frequency or magnitude of drivers of deterioration need to be incorporated into the site's management strategies. Further research is needed to understand how projected climatic scenarios could impact the rate and nature of deterioration occurring on earthen heritage and also to understand how environmental forces interact causing synergistic effects (Brown et al., 1990; Rainer, 2008). This research into synergistic effects is vital to further allow comparison of results from laboratory and field-based studies on earthen deterioration.

4.5 Conclusion

Environmental forces can cause deterioration to earthen heritage. This study utilised a unique opportunity to undertake deterioration experiments at the remote and understudied World Heritage site of Suoyang Ancient City, China. The tests were performed by exposing a test wall to clean wind, sediment-laden wind and wind-driven rain and resulted in the formation of incipient deterioration features which could be

mapped on to features seen on the historic walls. Clean wind caused the least deterioration and only removed loose material from protruding areas of the wall, while sediment-laden wind caused pitting. Wind-driven rain caused the greatest deterioration with the formation of incipient gullies down the wall face. However, the low frequency of rainfall at Suoyang is likely to limit the extent to which rainfall can cause deterioration at the site, whereas the almost continual nature of erosive wind events suggests that wind may play an important role in causing deterioration even though it only has a low magnitude impact. The formation of the incipient features suggest that this field based experimental method provides a more realistic deterioration mechanism than using small samples in the laboratory, whilst still being able to control and measure the impact of individual environmental conditions on earthen heritage deterioration. Further research is needed to understand how climate change will affect the environmental forces operating at Suoyang as increases in the frequency of rainfall or the speed of the wind could result in faster rates of earthen heritage deterioration. These findings show that conservation strategies at rammed earth sites need to address the impact of clean wind, sediment laden wind and rain to effectively minimise deterioration.

4.6 Chapter 4: Summary and implications

Results from the controlled deterioration field experiment showed that:

- (i) wind, sediment laden wind and wind-driven rain cause distinct incipient deterioration features, with the formation of polishing, pitting and gullying.
- (ii) the extent of deterioration is dependent on the intensity of the environmental process: higher intensities result in greater material loss.
- (iii) the forms of the incipient features on the test wall show strong similarities with more developed deterioration features on the historic walls of Suoyang.

The different forms of the deterioration features produced in this experiment suggest that deterioration features already present on earthen heritage could be used to infer causal environmental drivers of deterioration. This could provide a non-destructive approach for assessing drivers of deterioration at multiple locations within an earthen heritage site.

Further consideration of the extent and severity of deterioration features, as well as the rate of formation and the persistence of features is needed to assess the relative importance of, and explore the interactions between, multiple environmental drivers on earthen heritage.

5 The importance of wind as a driver of earthen heritage deterioration in dryland environments (Paper 2)

Submitted as: Richards, J., Viles, H. and Guo., Q. The importance of wind as a driver of earthen heritage deterioration in dryland environments. To *Geomorphology*.

Highlights

- Geomorphological signatures reveal drivers of earthen heritage deterioration
- High frequency of wind events in drylands causes substantive cumulative impact
- Wind-driven deterioration features typically have low persistence
- Wind is an important driver of earthen heritage deterioration but easily overlooked

Abstract

Dryland regions are exposed to extreme environmental conditions that create hotspots of weathering and erosion. Many earthen heritage sites are located in these dryland regions and experience extensive deterioration driven by interactions with environmental processes, however previous research has focused largely on the role of rain as a driver of deterioration. This study combines approaches from geomorphology with understandings of earthen materials from heritage science to investigate the relative importance of wind and rain in driving earthen heritage deterioration in drylands. We use geomorphological signatures to infer the environmental histories of earthen walls with a range of known ages at Suoyang Ancient City, China, using semi-quantitative deterioration assessments. We find rain-driven deterioration features to be associated with the loss of larger volumes of material and to have higher persistence than wind-driven deterioration features. However, we argue that the high frequency nature of wind events means that wind is an important initiator of deterioration across the site. In addition, walls exposed to the prevailing wind are dominated by wind-driven deterioration features. Outcomes from this study present an opportunity for earthen heritage conservation to investigate potential strategies to minimise wind speed at earthen heritage sites in drylands.

Key Words: earthen heritage, deterioration, frequency, magnitude

5.1 Introduction

In dryland regions, extreme environmental conditions can cause hotspots of weathering and erosion to occur (Shao et al., 2013; Viles and Goudie, 2013, 2007; Xie et al., 2007a). Strong winds can remove material through deflation and abrasion (Mao et al., 2015; X. D. Wang et al., 2010), while sporadic rainfall events can erode material through processes such as splash, rill, gully and sheet erosion (Beckett et al., 2020; Luo et al., 2019). There is a long history of research on the impact of environmental drivers on in-situ rock breakdown in drylands (Huinink et al., 2004; Loughlin, 1931; Momeni et al., 2015; Schaffer, 1932) and the evolution of landforms such as yardangs (Goudie et al., 1999; Li et al., 2016; Pelletier et al., 2018; Ward and Greeley, 1984). However, notably less research has investigated the impact of environmental drivers on building materials used in dryland regions.

Understanding the drivers of deterioration for earthen building materials in dryland regions is highly important as, due to the widespread availability of earth as a building material, many earthen heritage sites are found there (WHEAP, 2012). The value of many earthen sites is linked to the presence of authentic materials (Richards et al., 2018), but these materials are currently experiencing extensive deterioration (Pu et al., 2016a; Richards et al., 2020; Shao et al., 2013; X. D. Wang et al., 2010; Xie et al., 2007a). Earthen materials have been found to have a low durability to environmental processes (Beckett et al., 2020). For example, rain and wind-driven rain (hereafter both referred to as rain) can weaken cementing material between particles, caused by dissolution and hydration reactions of key compounds (Richards et al., 2019b; Shao et al., 2013). Clean wind can deflate loose earthen material (Richards et al., 2019b). If the wind is sediment

laden, the impact of airborne particles hitting the earthen material can cause grains of earthen material to be loosened or to break off from the parent material resulting in abrasion (Mao et al., 2015, 2008; Richards et al., 2019b; X. D. Wang et al., 2010).

Without the development of conservation strategies that effectively reduce rates of material loss at these sites, further damage to earthen heritage sites is inevitable.

Consequently, there is an urgent need to understand the relationships between environmental processes and earthen heritage deterioration. In particular, we need to understand: (i) the nature and distribution of environmental drivers of deterioration, (ii) the frequency and magnitude at which each driver occurs and (iii) the persistence of resultant deterioration features.

Earthen heritage research has predominantly focused on identifying drivers of deterioration but has not yet addressed the relative extent to which these drivers cause the loss of historic material (Du et al., 2017; Pu et al., 2016a; Shao et al., 2013). This lack of research is caused, in part, by limitations in many experimental setups, with experiments investigating the impact of single environmental drivers in isolation from other drivers (Luo et al., 2019); not being run for long enough to allow deterioration features that form at slower rates to develop (Pu et al., 2016a; Richards et al., 2019b); not capturing the complexity of on-site conditions (Mao et al., 2015); and overlooking the important differences in the magnitude and frequency of events (Bruno et al., 1968). Similar methodological challenges have also been faced in geomorphology. In response to these challenges, geomorphologists have used geomorphological signatures (the palimpsest of weathering or erosional features present on a given surface area) to infer environmental histories over a range of scales from sand grains to boulders to landscapes (Bourke et al., 2007; Ehlmann et al., 2008; Lancaster, 1995; Viles, 2001).

In this paper, we apply approaches used in geomorphology, which assess impacts of weathering and erosion on rock and soil surfaces, and apply them to earthen heritage. We use geomorphological signatures as a method to investigate the relative importance of environmental drivers of deterioration on earthen walls with a range of known ages. In particular, this study addresses the following questions:

- i) To what extent do wind and rain drive deterioration processes on earthen heritage in arid and semi-arid areas?
- ii) How should understanding of these interactions inform conservation strategies for earthen heritage?

Earthen heritage is constructed from a range of materials that each have unique interactions with environmental drivers of deterioration (e.g. adobe, rammed earth, cob). To reduce complexity, this study focuses on heritage sites constructed of rammed earth. This is justified as: (i) many earthen sites in dryland regions are constructed of rammed earth; (ii) many rammed earth sites are experiencing widespread deterioration; and (iii) rammed earth has been understudied in comparison to other earthen materials such as adobe (e.g. Brown et al., 1979; Guerrero, 2002; Illampas et al., 2013; Oliver et al., 2000; Selwitz et al., 1990; Taylor, 1990).

Rammed earth is constructed by compacting layers of raw earth within a temporary frame to create a compacted, solid material. Historically compaction was undertaken using a ramming tool resulting in a distinctive layering pattern. Once the desired height of the wall was reached, the frame was moved along and the process repeated to create a continuous wall. In particular, this paper focuses on the understudied and remote site

of Suoyang Ancient City, one of over 400 earthen sites located in northwest China, many of which are experiencing extensive deterioration (Mao et al., 2015).

5.2 Material and methods

5.2.1 Study site: Suoyang Ancient City

Suoyang Ancient City (锁阳城), hereafter known as Suoyang, is located in Gansu Province, north west China, on the ancient Silk Road. It is an archaeological site built from rammed earth during the Han (206 BC–220 CE) and Tang (618 – 907 CE) dynasties and abandoned ~400 years ago (Xie et al., 2007a). The site covers over 1 km² and consists of inner city walls (approximately 500 m²; Figure 5.1a), outer city walls, a monastery (Figure 5.1b), stables, archery platforms and an extensive irrigation system (UNESCO, 2014). In 2014, Suoyang was enlisted as one of 33 sites that form the Silk Roads World Heritage Site. The site exhibits a variety of deterioration features such as polishing, pitting, slurries and scouring as well as formation of cracks, gullies, slumps and collapses (Richards et al., 2019b; Appendix E), which have similarities with weathering and erosional features found on rock walls (Messenzehl et al., 2018), cliff faces (Kuenen, 1948) and earthen hill slopes (Xu et al., 2017).

The site has a continental semi-arid climate with temperatures exceeding 35 °C in summer and falling below -30 °C in winter (UNESCO, 2014). Precipitation is seasonal with most falling during spring and summer. Between 1986 and 2005, the average annual precipitation was 49 mm but ranged from 33 to 74 mm with the maximum single rainfall event recorded at 30 mm. Wind speed and direction is highly seasonal with strong easterlies occurring in the summer months (Dunhuang Academy, unpublished).

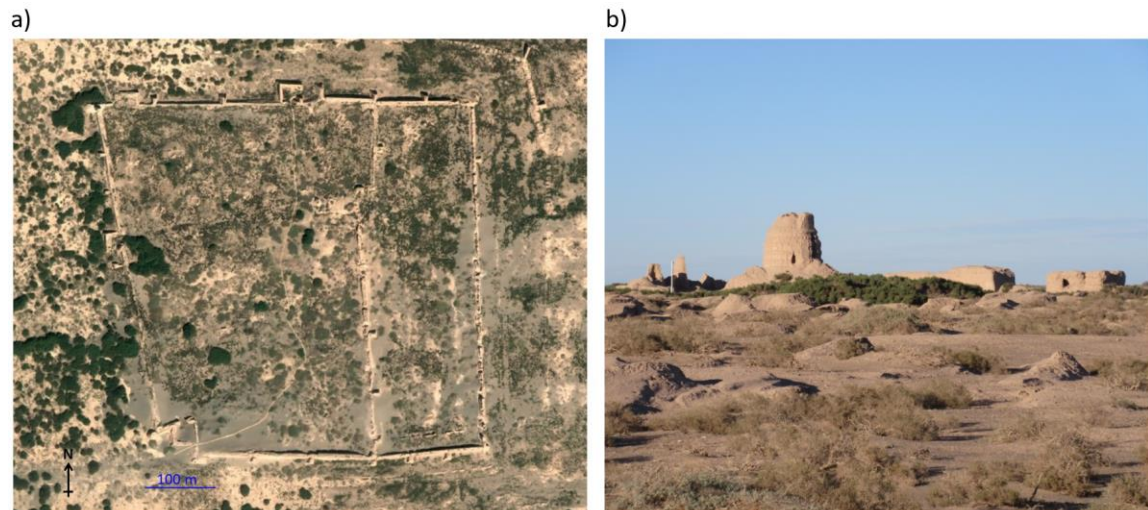


Figure 5.1: The site of Suoyang Ancient City a) from above (Credit: Google Earth) and b) the monastery (Credit: author's photo).

Suoyang's remote location and harsh climate have precluded much scientific research.

However, since 2015, Dunhuang Academy have established an experimental test area to the east of the main site. Two sets of test walls (large and small) have been built in this experimental area, allowing a range of tests to be undertaken on and around earthen walls without harming the historic material. As such, Suoyang provides a unique opportunity for the investigation of environmental and deteriorative processes to be studied at a remote earthen site, which has many similarities to other earthen sites in this area.

5.2.1.1 Experimental area: Test walls

Both sets of test walls in the experimental area were used in this study. The set of small test walls was built in April 2015. We used the wall from the set that was built to replicate the material properties of the historic walls at Suoyang (Figure 5.2). This small test wall faces north and was built against a yardang using loessic soil taken from areas around Suoyang, with similar particle size distribution to the historic material. The wall was constructed using traditional ramming techniques as described above. The wall is formed of six layers and measures 64 cm high and 76 cm wide, with a density of 1.70 g

cm^{-3} . The wall has been exposed to the environment for three years and is now assumed to be in equilibrium with environmental conditions. For more information see Richards et al. (2019b).

Four large test walls (210 x 300 x 100 cm) were also built by Dunhuang Academy in July 2017, perpendicular to the prevailing easterly wind. These walls were constructed in a similar manner to the small test wall with two different densities representing a deteriorated (1.65 g cm^{-3} – Wall 1 and 2) and non-deteriorated state (1.75 g cm^{-3} – Wall 3 and 4; Figure 5.2). These walls have been exposed to the environment for more than a year and are also assumed to be in equilibrium with the environment.

Fieldwork was undertaken in August 2018 as part of a wider project investigating potential conservation methods for Suoyang. Data collection focused on a range of locations on the historic inner city walls and on the test walls in the experimental area (Figure 5.2). During the fieldwork, on the 14th – 15th August, a 36-hour storm occurred with strong westerly winds gusting over 17 ms^{-1} and heavy rain.

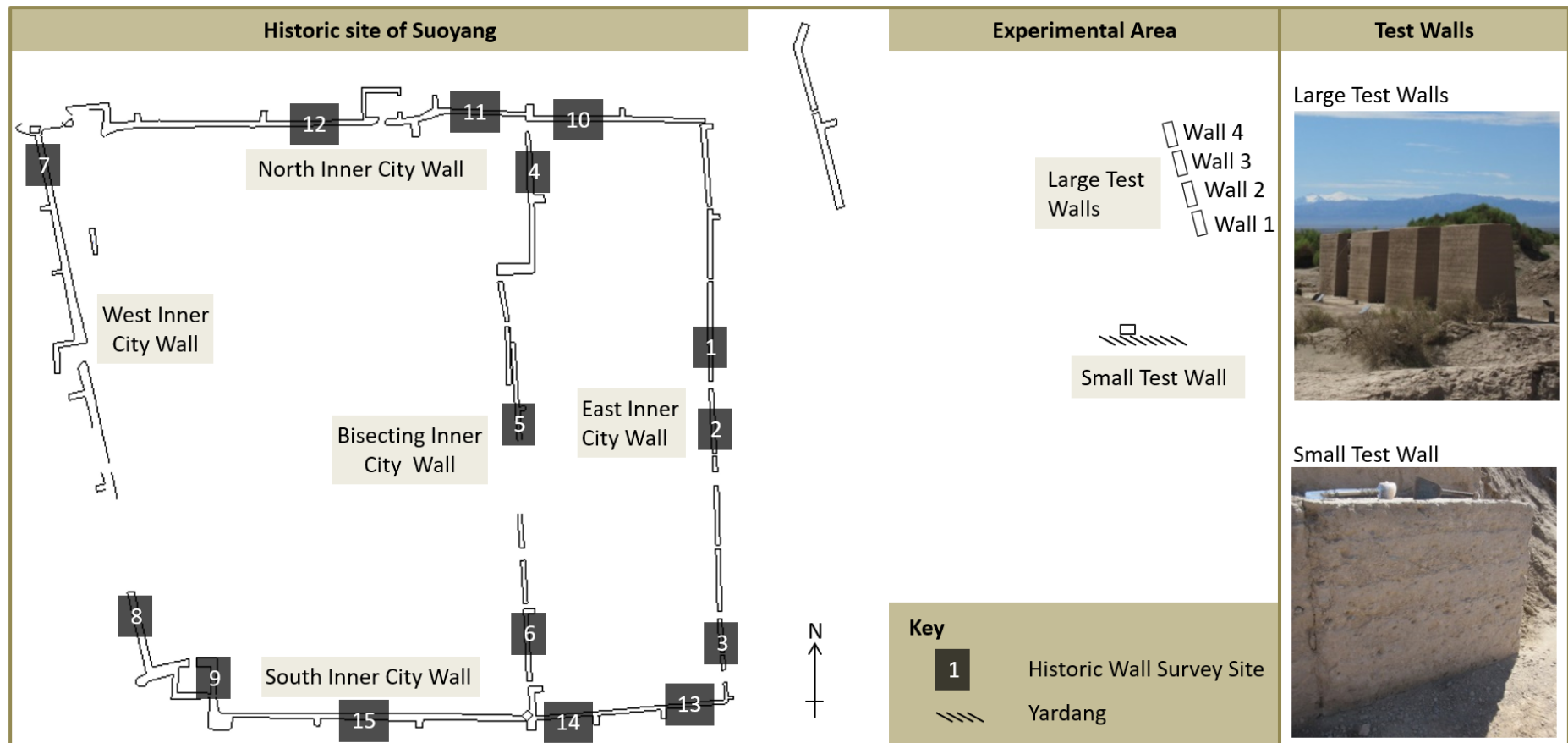


Figure 5.2: A plan view of Suoyang showing the location of the small test wall, large test walls and inner city walls. Sites for expert deterioration survey assessment on the inner city walls are indicated.

5.2.2 Approach

In this study, we assessed the relative importance of wind and rain as drivers of deterioration by using semi-quantitative visual methods to characterise the type and severity of deterioration features associated with wind and rain present on the wall face (Mottershead, 2000; Wright, 2002). Together these features formed a geomorphological signature that was used to infer the deterioration history of Suoyang (Figure 5.3) (Ehlmann et al., 2008).

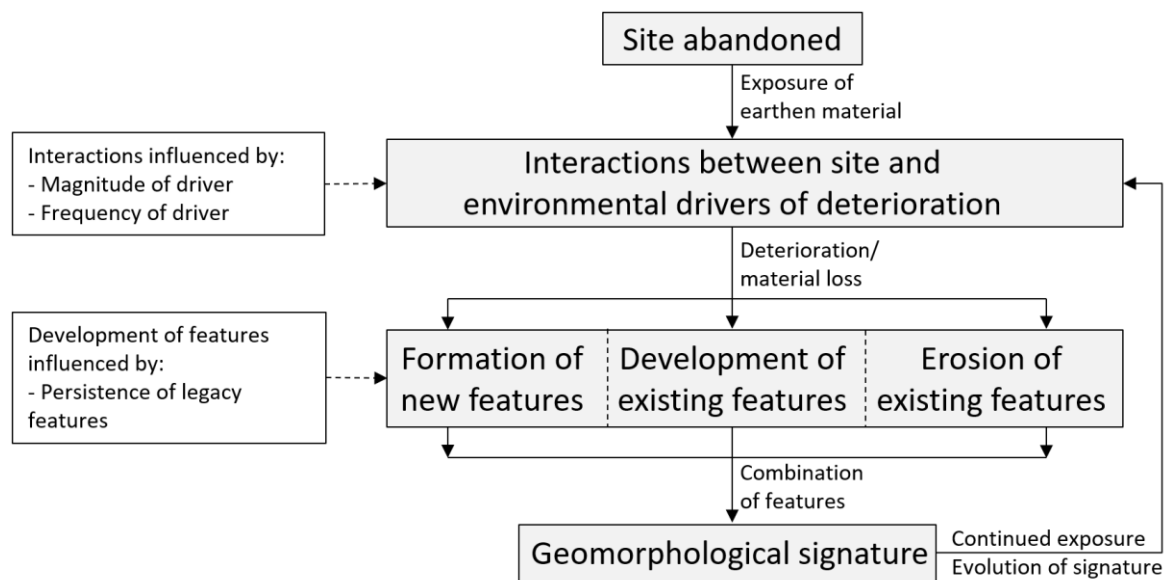


Figure 5.3: Our approach for assessing geomorphological signatures through the formation of deterioration features

Research suggests that geomorphological signatures are likely to be influenced by: (i) the frequency and magnitude of environmental drivers (Brunsden and Thornes, 1979; Goudie and Viles, 1999; McKay et al., 2009), and (ii) the persistence of deterioration features in the face of subsequent events, where persistence refers to the duration of time a deterioration feature remains visible after its formation (Figure 5.3) (Bourke et al., 2008). However, in the earthen heritage literature, there has been little discussion of these concepts.

To assess geomorphological signatures on earthen heritage, we surveyed deterioration features present on test and historic walls that had been exposed to deteriorative environmental conditions for different lengths of time. At all survey sites, deterioration features were identified using a key developed by the authors using information collected from a preliminary visit to the site in August 2017 (Table 5.1). The severity of identified features was ranked on a four-point scale with respect to the feature's spatial coverage: absent (-), present in a localised area (*), present in multiple areas (**) or extensive coverage (***)

We used abductive reasoning to determine the environmental process(es) likely to have caused the deterioration features. This reasoning was informed by literature (see Table 5.1) and the authors' previous experimental work and experience (e.g. Richards et al., 2019b) to minimise any potential issues caused by equifinality.

Table 5.1: Descriptions and the inferred causes of deterioration features at Suoyang.

Deterioration feature	Description	Inferred Cause	Literature
Wind-polishing	Surface smooth with all loose material removed. No grooves or scouring marks.	Clean wind	(Shao et al., 2013) (Lancaster, 1984)
Sand-polishing	Surface smooth with all loose material removed. Thin scouring lines are present. Lines are normally horizontal or in the direction of the wind flow around the wall.	Sediment laden wind	(Laity, 2011) (Laity, 2009)
Rounded corners	Corners and edges of walls (both vertical and on the wall top) are rounded with no distinct sharp edge.	Clean wind Sediment laden wind	(Fujii et al., 2009)
Scouring at base	Distinct grooved lines at the base of the wall in the direction of the wind flow around the walls. Grooved lines are generally thicker than those found higher up the wall. Some scouring material may also be present.	Sediment laden wind Fast clean winds	
Pitting/hollowing	Removal of material from a localised area. The surface is normally rough and concave.	Sediment laden wind Fast clean winds	(Shao et al., 2013)
Flaking	Thin surface layer of material detached from main body of wall and peeling off in flakes.	Wind-driven rain Vertical rain	(Bruno et al., 1968) (Cui et al., 2019a)
Slurry	Crust on wall surface formed down the wall face. Generally smooth surface.	Wind-driven rain Vertical rain	(Shao et al., 2013) (Crosby, 1983)
Gully	Vertical indent or gorge into the wall surface. Normally occurs below a nook or low point in the wall height.	Vertical rain Wind-driven rain	(Du et al., 2017) (Bruno et al., 1968)
Outwash slope	Sediment at the base of the wall fanning away from the wall. Usually poorly sorted with consolidated lumps of earthen heritage present.	Wind-driven rain Vertical rain	
Turreting and wall collapse	Substantial or complete loss of material from wall causing stepped changes in wall height.	Wind-driven rain Clean wind Sediment laden wind	(Bruno et al., 1968)

5.2.2.1 Assessment of geomorphologic signatures on small test wall

On the small test wall, field experiments were run to produce geomorphic signatures under controlled experimental conditions. The wall was cleaned to remove any naturally occurring deterioration features already present and then exposed to clean wind, sediment laden wind and rain representative of conditions representative of conditions experienced at the site over a period of days to months (Richards et al., 2019b). The wall was scanned using a handheld Creaform Handy SCAN 700 3D™ laser scanner (0.2 mm accuracy, 0.050 mm resolution) before and after each experimental run. The surface spatial grid data was analysed using Geomagic Control, with the point cloud being processed into a 3D mesh. Pre- and post-test meshes were aligned and the topography compared to identify any changes to the wall surface (Barton, 2009). Any changes to the wall surface were then assessed using the deterioration key (Table 5.1) and the extent of the deterioration features ranked. For more information on the experimental setup see Richards et al. (2019).

5.2.2.2 Assessment of geomorphologic signatures on large test walls

At the time fieldwork was undertaken, the large test walls had been exposed to environmental processes for approximately 1 year. Visual assessments were undertaken on each vertical face of the test wall and analysed for notable deterioration features (Rothert et al., 2007) using the deterioration key (Table 5.1).

5.2.2.3 Assessment of geomorphologic signatures on historic inner city walls

The historic inner city walls have been exposed to environmental processes over several centuries, having been constructed over a millennia ago and abandoned approximately 400 years ago (UNESCO, 2014). To assess the variability in deterioration features on the

historic walls, the inner city walls were divided into five wall sections: north, south, east, west and bisecting (central). Three sites on each wall section were selected using a combination of systematic and opportunistic sampling to ensure that, where possible, the full length of each wall was surveyed (Figure 5.2 – sample sites are numbered 1 to 15). At each survey site, vertical wall faces were assessed for deterioration features (Table 5.1).

5.3 Results

5.3.1 *Small test wall*

After the field experiment, geomorphological signatures on the small test wall were composed of a limited number of deterioration features (one to three) at an early stage of formation (Table 5.2). Clean wind caused small amounts of loose material to be removed from protruding areas resulting in polishing (Figure 5.4a). Sediment laden wind caused loose material to be removed from the surface, as well as the abrasion of small grains of material, resulting in incipient pitting (Figure 5.4b). Rain caused soil particles to be entrained and transported down the wall face resulting in incipient gullying (Figure 5.4c). The severity of the deterioration features varied, with the clean wind causing minimal, localised impacts while the sediment laden wind and rain caused more extensive deterioration.

Table 5.2: The types and severity of deterioration features present on the small test wall, large test walls and inner city walls

			Wind					Rain				Both
Aspect	Location/sample site		Wind-polishing	Sand-polishing	Rounded corners	Scouring at base	Pitting/ hollowing	Flaking	Gully	Slurry	Outwash slope	Turretting
N/A	Small test wall: Wind		*	-	-	-	-	-	-	-	-	-
	Small test wall: Sediment laden wind		*	*	-	-	**	-	-	-	-	-
	Small test wall: Rain		-	-	-	-	-	-	**	-	-	-
East	Large test wall 1		*	-	*	*	-	**	-	-	-	-
	Large test wall 2		*	-	*	*	-	**	-	-	-	-
	Large test wall 3		-	-	*	*	-	*	-	-	-	-
	Large test wall 4		-	-	*	*	-	*	-	-	-	-
West	Large test wall 1		-	-	*	-	-	***	-	-	*	-
	Large test wall 2		-	-	*	-	-	***	-	-	*	-
	Large test wall 3		-	-	*	-	-	***	-	-	*	-
	Large test wall 4		-	-	*	-	-	***	-	-	*	-
East	East inner city wall	Site 1	**	*	***	***	***	-	*	*	*	***
		Site 2	*	*	**	**	**	-	-	*	**	***
		Site 3	**	**	**	**	**	-	*	*	*	***
	Bisecting inner city wall	Site 4	**	***	**	-	*	-	*	**	**	-
		Site 5	**	***	**	*	*	-	-	*	**	**
		Site 6	*	***	***	-	**	*	-	**	**	*
	West inner city wall	Site 7	**	**	**	-	**	-	*	**	-	-
		Site 8	**	***	***	*	**	-	-	**	*	-
		Site 9	**	***	**	-	***	-	*	*	-	-
West	East inner city wall	Site 1	-	-	*	*	-	*	-	***	-	***
		Site 2	-	-	*	*	-	**	-	***	**	***
		Site 3	-	-	*	*	-	-	**	***	*	***
	Bisecting inner city wall	Site 4	-	-	*	-	-	**	-	***	***	-
		Site 5	-	-	*	-	-	*	-	***	***	**
		Site 6	-	-	*	-	-	***	-	***	***	*
	West inner city wall	Site 7	-	-	-	-	*	**	-	***	*	-
		Site 8	-	-	**	-	-	**	*	***	-	-
		Site 9	-	*	*	-	-	*	-	**	-	-
Internal	North inner city wall	Site 10	*	**	***	-	**	-	**	**	**	-
		Site 11	*	**	***	-	-	**	*	***	***	-
		Site 12	-	-	**	-	*	*	-	**	***	-
	South inner city wall	Site 13	**	***	**	-	**	*	*	**	**	-
		Site 14	*	***	**	-	***	-	*	**	**	-
		Site 15	*	**	**	*	**	**	-	***	***	-
External	North inner city wall	Site 10	*	***	*	-	**	-	*	**	**	-
		Site 11	**	***	*	-	**	-	-	***	**	-
		Site 12	**	***	**	-	**	*	-	***	*	-
	South inner city wall	Site 13	*	**	*	-	***	-	*	**	**	-
		Site 14	*	*	**	-	**	*	*	**	**	-
		Site 15	***	***	**	*	**	-	*	**	*	-

Key

-	absent
*	present in a localised area
**	present in multiple areas
***	extensive coverage

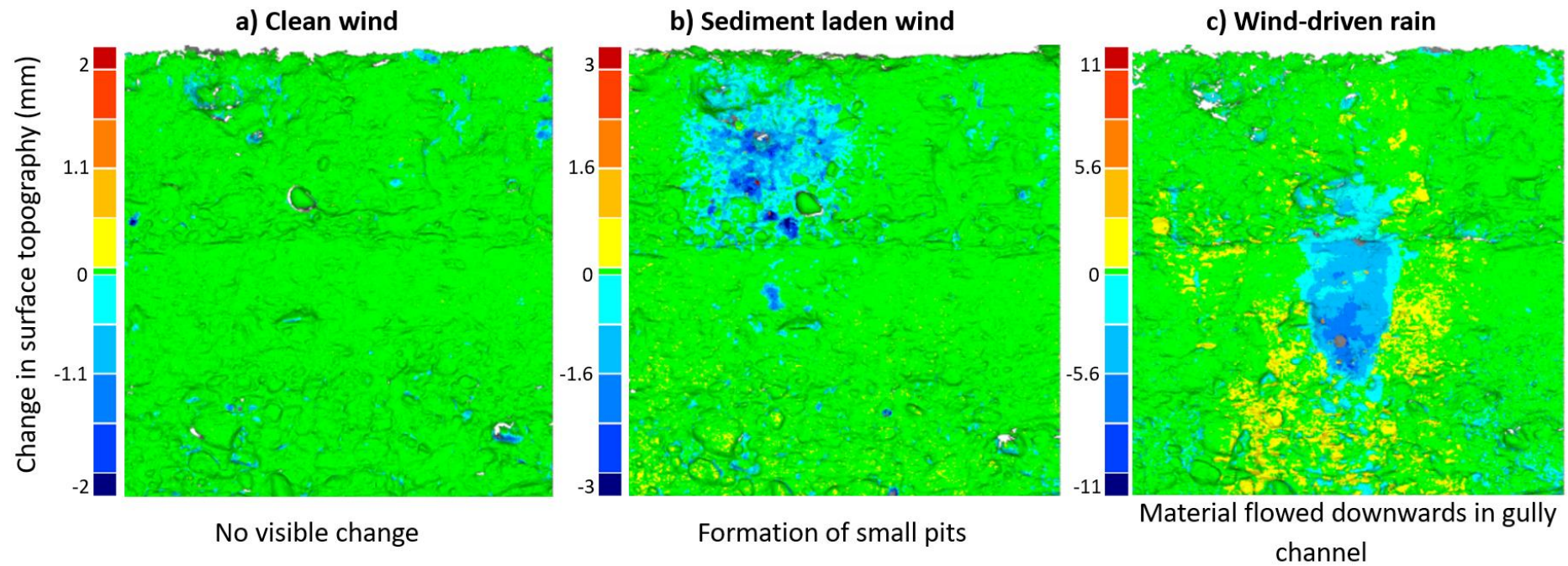


Figure 5.4: Deviation maps showing change in surface topography (mm) after being exposed to a) wind, b) sediment laden wind and c) rain. Note the different scales for each deviation map. Adapted with permission from Richards et al. (2019b).

5.3.2 *Large test walls*

After exposure for 1 year, the geomorphological signatures on the large test wall each comprised three to four deterioration features associated with both wind and rain events (Table 5.2). All four test walls exhibited features including a slight rounding of corners and scouring around the base of the walls in an east-west direction (Figure 5.5a and b). On the western side, flaking was present across the entire wall face. On the eastern side there was variation in the deterioration features present across the wall face. On the two lower density walls (Walls 1 and 2), there was a notable change in the extent of flaking with height. On Wall 1, there was extensive flaking at the base of the wall to around 50 cm above the ground (Figure 5.5c). On Wall 2, there was minimal erosion at the base of the wall, with flaking only occurring around 1.75 m from the ground. This lack of flaking below 1.75 m is likely to be associated with the presence of a yardang to the east of the wall, approximately 1.5 m high, blocking the strong easterly winds from interacting with the base of Wall 2. On the two higher density walls (Walls 3 and 4) there was some less severe, patchy flaking occurring on the eastern side.

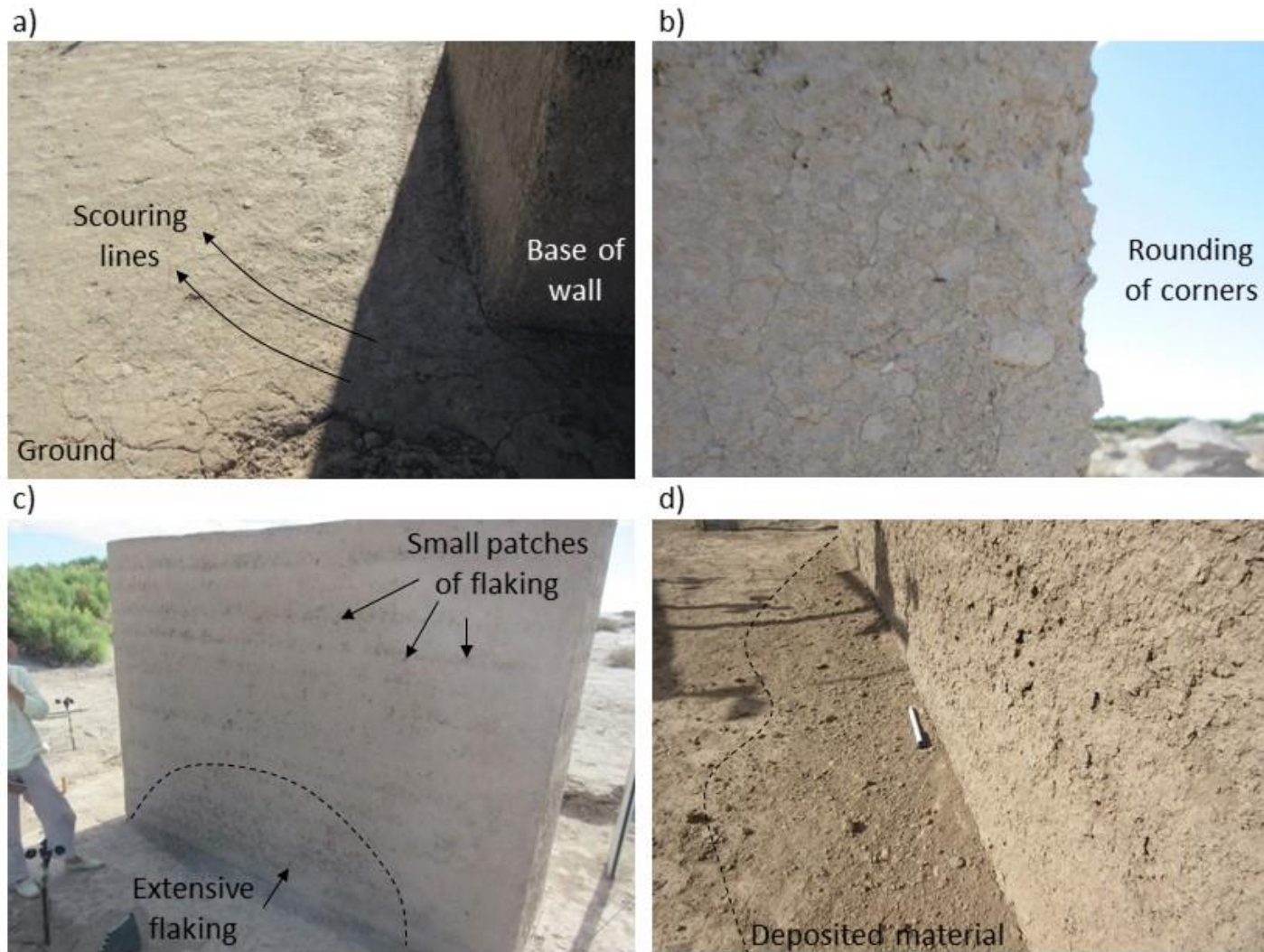


Figure 5.5: Deterioration features found on the large test walls after one year exposed to the environment at Suoyang: a) scouring around the base of the test walls, b) the rounding of the test wall corners, c) the variation in flaking on the eastern side of Wall 1 and d) the deposited material at the base of the west side of Wall 1, much of which was deposited after a 36 hour storm event.

Development of deterioration features in real time was observed on the large test walls during the storm event on 14-15th August 2018. The storm caused a notable volume of material, composed of a range of grain sizes, to be deposited at the base of the walls forming a small outwash slope. This was especially visible on the west side, facing the prevailing storm direction, where the deposited material extended outwards for almost 50 cm in some areas (Figure 5.5d). After 24 hours the wall surfaces had dried but the subsurface was still likely to be damp. This rapid surface drying could cause the earthen material to be vulnerable to deterioration due to the swelling and contraction of clays within the soil matrix (Velde, 2008).

5.3.3 Historic walls

The greatest variety in deterioration features was found on the historic walls with each signature comprising five to eight overlain deterioration features associated with both wind and rain events (Table 5.2). The variability of deterioration around the site was also captured with the geomorphological signature varying significantly between different sections of the inner city wall and also within individual sample sites (Figure 5.6).

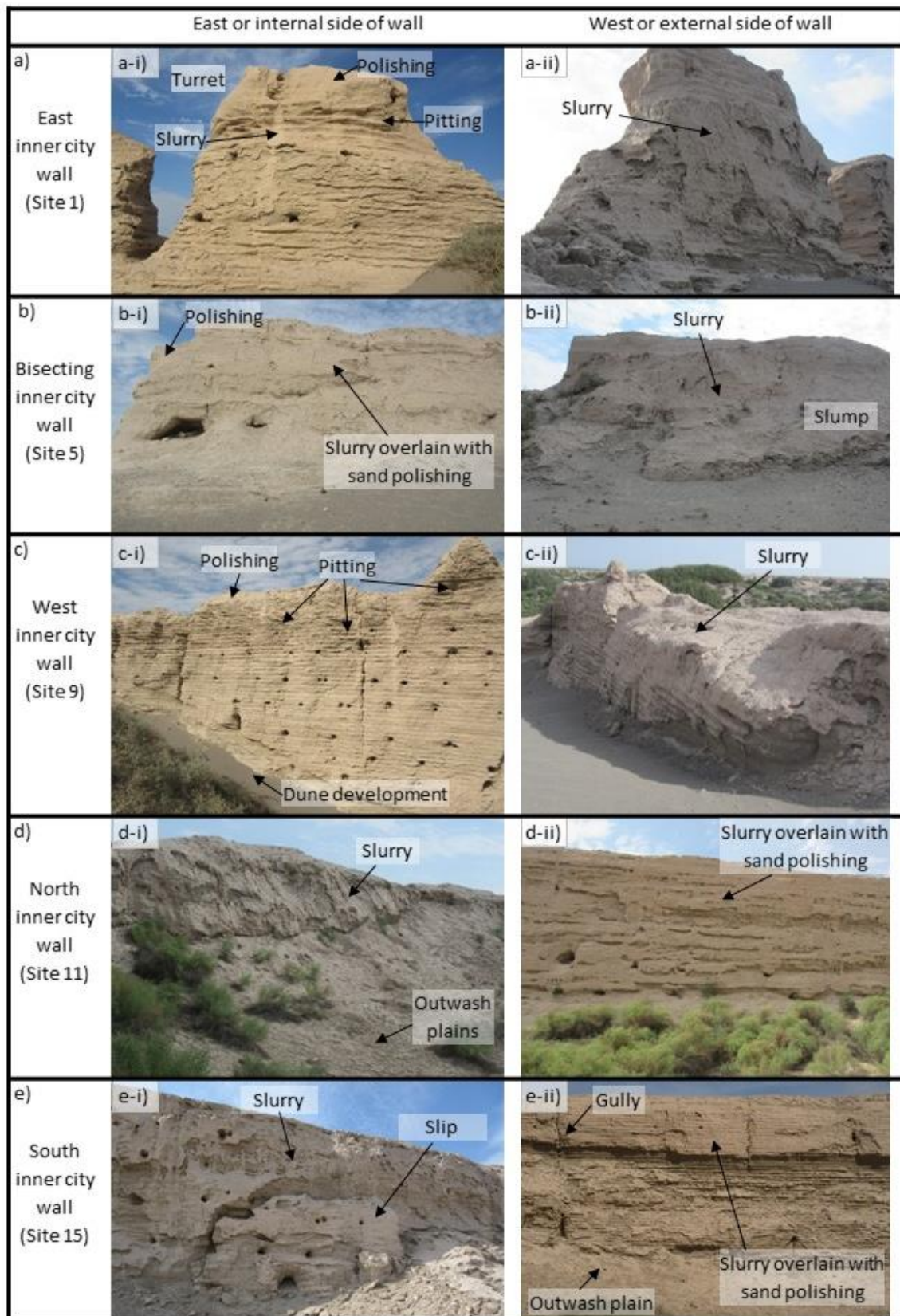


Figure 5.6: Deterioration around Suoyang at the a) East, b) Bisecting, c) West, d) North and e) South inner city wall. Deterioration on the east or internal wall face is shown in (i) and west or external wall face is shown in (ii).

East inner city wall

The east inner city wall was degraded into turret shaped sections with some sections becoming free standing (Table 5.2). On the east side of the east inner city wall there was extensive hollowing and deflation with rammed earth layers clearly visible across the majority of the wall face (Figure 5.6a-i). At the base of the walls there was also extensive scouring and rounding of corners, especially on faces between wall sections. At the top of the walls there were notable patches of wind polishing and some small sections of slurry. The slurry tended to be located under small faults in the wall top and in some cases formed narrow gullies down the wall face. At the base of the wall there tended to be a small outwash plain.

On the west side of the east inner city wall, slurry covered almost all areas with multiple layers being visible on some wall sections (Figure 5.6a-ii). Gullies were also present and were deeper than on the east side of the same wall section. At the base of the wall, slurry had been undercut especially on wall sections which had a dune forming against the wall.

Bisecting inner city wall

The bisecting inner city wall was taller and the wall sections were more continuous (less turret-like) with fewer collapses than the east inner city wall (Table 5.2). On the east side of the bisecting inner city wall, extensive wind and sand polishing and rounded corners was present (Figure 5.6b-i). In addition, there were areas of slurry, some of which was overlaid with sand polishing. In areas where slurry had been eroded, either by undercutting or flaking off, material had been deflated. Gullies were present on some areas of the wall, predominately forming where cracks were present in the wall. The west side of

the bisecting wall was notably more slumped with large dunes abutting the wall (Figure 5.6b-ii). There was extensive slurry across the wall surface and large outwash plains at the base.

West inner city wall

The west inner city wall was almost continuous. On the east side, wind and sand polishing, rounding of corners and deflation of material with some slurry and gullying were present at the north and south end, and there was extensive dune development almost burying the walls in some places in the centre (Table 5.2; Figure 5.6c-i). On the west side there was extensive dune development towards the centre of the wall. The exposed areas at the north and south end of the wall exhibited large amounts of slurry over the walls, deep gullies running down the wall face and out wash plains at the base of the walls (Figure 5.6c-ii).

North inner city wall

The north inner city wall was continuous (Figure 5.6d). The internal wall had extensive slurry coverage in some areas with large outwash plains at the base of the wall (Table 5.2; Figure 5.6d-i). Corners along the wall were rounded but there was variation in the extent to which there was deflation, dune development and gullying on the walls. Some areas showed a palimpsest of deterioration features with sand polishing overlaying slurry.

The deterioration features along the external wall were similar except for around the fortification towers where slurry was more dominant on the leese side of the towers. On all

other areas, there was a thin slurry down the walls with sand polishing on top and shallow gullies down the wall with outwash fans at the base (Figure 5.6d-ii).

South inner city wall

The south inner city wall was also continuous. However, parts of the internal wall showed evidence of collapse and had thick slurry occurring along the entire length with shallow outwash plains along the base of the wall (Table 5.2). Over the top of the crust, there was notable horizontal wind polishing (Figure 5.6e-i). In addition, deep gullies were present with outwash fans at the base of the gully. The deterioration features on the external wall were similar to those found on the external north inner city wall: in all areas except for around fortification towers there was thin slurry overlaid with sand polishing (Figure 5.6e-ii).

5.4 Discussion

We used geomorphological signatures present on the test and historic walls at Suoyang to investigate the relative importance of wind and rain as drivers of earthen heritage deterioration. By combining the geomorphological signature data from the test and historic walls (Table 5.2, Figure 5.4 -Figure 5.6), Table 5.3 ranks the relative importance of wind- and rain-driven deterioration features over different exposure periods using a five-point scale. The relative importance was assessed with regard to:

- (i) the nature and distribution of features.

Volume: A value of '1' was assigned to features formed with the erosion/ deposition of small (cm^3) quantities of sediment off the wall surface, while '5' was assigned to features formed with the erosion/ deposition of large (m^3)

quantities of sediment that threaten the structural integrity of the wall.

Spatial coverage: A value of '1' indicated a presence on localised areas, while '5' indicated complete, widespread coverage.

- (ii) the frequency and magnitude of deteriorative events required to drive a feature's formation.

Number of events: A value of '1' was assigned to features that formed after exposure to many deterioration events (100s), while '5' was assigned to features formed within a single deterioration event.

Time to formation: As deterioration events in dryland regions occur at different frequencies, deterioration features that form over long temporal periods (decades) were assigned a '1'. Features that form over short temporal periods (days) were assigned a '5'.

- (iii) the persistence of a feature to future deteriorative events.

Persistence: A value of '1' was assigned to features erased by subsequent deterioration events. '5' was assigned to features still present after numerous (100s) subsequent deterioration events.

Table 5.3: Comparing the nature and distribution, frequency and magnitude and persistence of wind- and rain-driven deterioration features on earthen heritage

		Wind-driven features					Rain-driven features				Both
		Rounded corners	Scouring at base	Sand polishing	Wind polishing	Pitting	Flaking	Slurry	Gully	Outwash slope	
Nature and distribution	Volume of material eroded or deposited during feature formation (1=small, 5=large)	1	1	1	1	2	2	3	4	4	5
	Spatial coverage of feature at Suoyang (1=localised, 5=widespread)	1	1	2	3	4	3	4	1	3	2
Frequency and Magnitude	Number of wind/rain events for feature to form (1=many events, 5=few events)	3	3	1	1	1	3	3	4	4	1
	Time period for feature to form in semi-arid regions (1=long period, 5=short period)	5	5	3	3	4	4	2	2	3	1
Persistence	Persistence of feature to wind events (1=low, 5=high)	-	-	-	-	-	3	4	4	3	5
	Persistence of feature to rain events (1=low, 5=high)	1	1	1	1	1	-	-	-	-	5

5.4.1 Nature and distribution of deterioration

In this study, we found substantive differences in the nature of deterioration features caused by wind and rain in terms of volume of material moved and spatial coverage (Table 5.3). As found experimentally on the small test wall, wind generally removed less material per event than rain (Figure 5.4). Similarly, on the historic and large test walls, wind-driven deterioration features were commonly formed with the loss of small volumes of material while a greater amount of material typically moved to form rain-driven features (Figure 5.5 and 5.6). These results correspond well with previous research that has also found that features such as polishing are commonly formed on areas where individual loose grains have been deflated, while features such as gullies

can transport large amounts of material en masse down the wall face (Mao et al., 2015; Richards et al., 2020, 2019b; X. D. Wang et al., 2010).

Of the deterioration features assessed in this study, turreting was associated with the greatest material loss. It was only found on the historic walls (Table 5.2) suggesting that this feature develops over longer temporal periods and on larger structures than other features such as polishing or rounding of corners.

The regular spacing of turrets along the east inner city wall further suggests that deterioration is focused on the weaker joints between the constructed sections of rammed earth, with interactions and feedbacks between gullying and wind deflation processes being vital in causing the development of turrets (Cui et al., 2019a; Du et al., 2017; Richards et al., 2020). Water run-off is likely to be promoted down fissures that have formed in the weaker boundary areas between wall sections. This runoff can result in the formation of gullies (Richards et al., 2019a). As gully channels deepen, winds can accelerate through these channels forming a zone of higher windspeeds, further abrading earthen material (Jaquin, 2008). Water runoff will also be promoted down these channels further incising them. This results in a positive feedback loop where boundary areas between wall sections are deteriorated, causing the development of free-standing turrets. However, the location of severe turreting on the eastern inner city wall, exposed to the prevailing wind, compared to the absence of turreting on any other inner city wall (Table 5.2), strongly implies that wind is likely to be the initiating factor in the formation of these large deterioration features.

The nature of deterioration is also likely to be affected by the construction and repair history of the earthen structure. The test walls have a known construction history, with

each wall being constructed at the same time and none have yet undergone any repairs. In contrast, the site of Suoyang was built over the Han (206 BCE-220 CE) and Tang (618 - 907 CE) dynasties and would have undergone repairs as required (UNESCO, 2014). As such, the historic walls present a more complex and dynamic construction process (Strlic, 2015). This is likely to result in more a greater range of deterioration features forming on the historic walls in response to the complex material structure. With the addition of new conservation treatments, this range of deterioration features could increase further.

Results from the test and historic walls show the distribution of other wind- and rain-driven deterioration features are constrained by spatial factors (Table 5.4). Both wind and rain features were seen to be controlled by the aspect of the wall, with prevailing climatic conditions strongly influencing the type of deterioration present on the historic and test walls. On both the test and historic walls, wall faces exposed to the prevailing wind direction tended to be dominated by wind-driven deterioration features, while wall faces exposed to the prevailing storm directions tended to be dominated by rain-driven deterioration (Figure 5.5 and 5.6; Table 5.2). The presence of wind-driven deterioration features was also seen to be strongly dependent on the spatial location across the wall face with respect to: the vertical height of the wall, the edge of the wall and the location of the saltation zone up the wall face (Table 5.4; Richards et al., 2020). The presence of rain-driven deterioration features is notably dependent on the location of cracks or joins in the earthen material (see Table 5.4 for further detail).

Table 5.4: Spatial controls on a) both wind- and rain-driven deterioration features, b) wind-driven deterioration features and c) rain-driven deterioration features

Spatial control	Reason	Impact
<i>a) Wind and rain</i>		
Aspect	The prevailing wind is easterly while the prevailing direction of storms is westerly	The presence of wind-driven deterioration features is dominant on the east wall faces while rain-driven deterioration features are dominant on the west wall faces
<i>b) Wind</i>		
Vertical height	Wind velocity increases with height from the ground	Presence of features formed by the deflation of loose material, such as wind polishing, are more commonly found near the top of the wall faces
Wall edge	Wind velocity is accelerated around the sides of objects	Acceleration can drive features such as the rounding of corners and also scouring round the base
Saltation zone	Sediment transport is concentrated within the first 40 cm above the surface	The kinetic energy of sediment laden wind can cause embedded particles to be loosened causing features such as pitting
Horizontal compaction layering	The density of earthen material is higher at the interfaces between rammed layers	Abrasional features such as pitting are concentrated on the areas of wall with lower density.
<i>c) Rain</i>		
Crack and joints	Faults in the earthen material can channel runoff down the wall face	Gully features are dominantly found at locations of wall weakness with depositional features such as outwash plains forming below

Once material was eroded from the parent material, wind typically entrained the earthen material, transporting it downwind, until it was either deposited in onsite dune formation or transported away from the heritage site. In contrast, material entrained in sheet or channelled runoff was typically redeposited further down the wall face or at the base of the wall (Richards et al., 2019b; Figure 5.6), analogous to sediment being

deposited from rivers that leave mountain ranges forming alluvial fans (Bull, 1977).

Consequently, products of rain-driven deterioration are likely to remain close to the parent material for longer than the products of wind-driven deterioration.

5.4.2 Magnitude and frequency of deterioration processes

Results from this study suggest that heavy rainfall events associated with dryland regions can drive the erosion of large volumes of earthen material (Table 5.2), but their sporadic, infrequent nature limits their overall impact (Figure 5.5). In contrast, individual wind events erode small volumes of earthen material but the high frequency of wind events in open, sparsely vegetated environments causes a significant cumulative impact. The cumulative impact of these low magnitude deterioration events is seen with extensive coverage of wind-driven deterioration features on walls facing the prevailing wind and also with wind controlling the location of larger features, such as turretting (Table 5.2). The low magnitude nature of wind as a driver of earthen deterioration means that over a recording period of days to months, these changes may not be visible and thus, further long-term studies are needed to quantify the impact of wind at earthen heritage sites.

5.4.3 Persistence of deterioration features

Findings from this study suggest that the persistence of deterioration at earthen heritage sites is dependent on the type of feature (Table 5.3). The small volume of material loss associated with the formation of wind-driven deterioration features on both the test and historic walls (Figure 5.4 – 5.6) suggests many wind-driven deterioration features, such as polishing, would only require small volumes of subsequent material movement to cause the original feature to be covered or eroded. In

addition, deterioration features, such as pitting, increase the surface area of the wall face and loosen particles from the parent material, thus increasing the area of earthen material exposed to further deterioration (X. D. Wang et al., 2010). Conversely, the larger volumes of material movement associated with the formation of rain-driven deterioration features, such as the gullies and outwash plains present on the historic walls (Figure 5.6), suggest that greater amounts of material are subsequently required to remove or cover over such features once they have formed. The transportation and redeposition of material in solution also alters the characteristics of the wall surface with the redeposited material forming a harder crust over the parent material (Cui et al., 2019a). This crust can act as a protective layer as well as promoting the deterioration of the layer of material behind the crust.

These differences in persistence are likely to affect the development of subsequent deterioration features— thus impacting the geomorphological signatures present on earthen heritage (Ehlmann et al., 2008). On the historic walls, we found evidence of rain-driven features forming over the top of wind-driven features (Table 5.2) indicating the potential for rain-driven features to replace evidence of wind-driven deterioration with a rain-driven geomorphological signature. In contrast, wind-driven features predominantly imprinted into the surface of the rain-driven feature without fully covering the underlying feature (Table 5.2). In cases such as scaling off where wind-driven deterioration causes the removal of rain-driven deterioration features, this process exposed fresh material without a geomorphological signature that could be associated with wind (Cui et al., 2019a).

Consequently, our results suggest that consideration of persistence is important for understanding how earthen sites exposed to environmental conditions evolve over time. Wind-driven deterioration features typically have low persistence, while rain-driven deterioration features typically has high persistence. Without considering the low persistence of wind-driven deterioration features, the short lifespan of such features could result in the impact of wind as a driver of deterioration being underestimated. As such, geomorphological signatures have to be interpreted in conjunction with the concept of persistence to ensure that the cumulative impact of low persistence features is fully considered.

5.4.4 The importance of wind as a driver of deterioration

Findings from this study highlight the importance of wind as a driver of deterioration due to the cumulative impact of high frequency/low magnitude wind events in dryland environments. The importance of this cumulative impact is shown in Figure 5.7. It was developed using the findings from Suoyang to provide a schematic portrayal of the formation and cumulative impact of wind- and rain-driven deterioration features on earthen heritage over time. The importance of wind as a driver of deterioration is likely to have been overlooked in previous research due to:

- (i) the low magnitude of deterioration caused by individual wind events in comparison to rain;
- (ii) the small volume of material loss associated with wind-driven deterioration;
and
- (iii) the low persistence of wind-driven deterioration features.

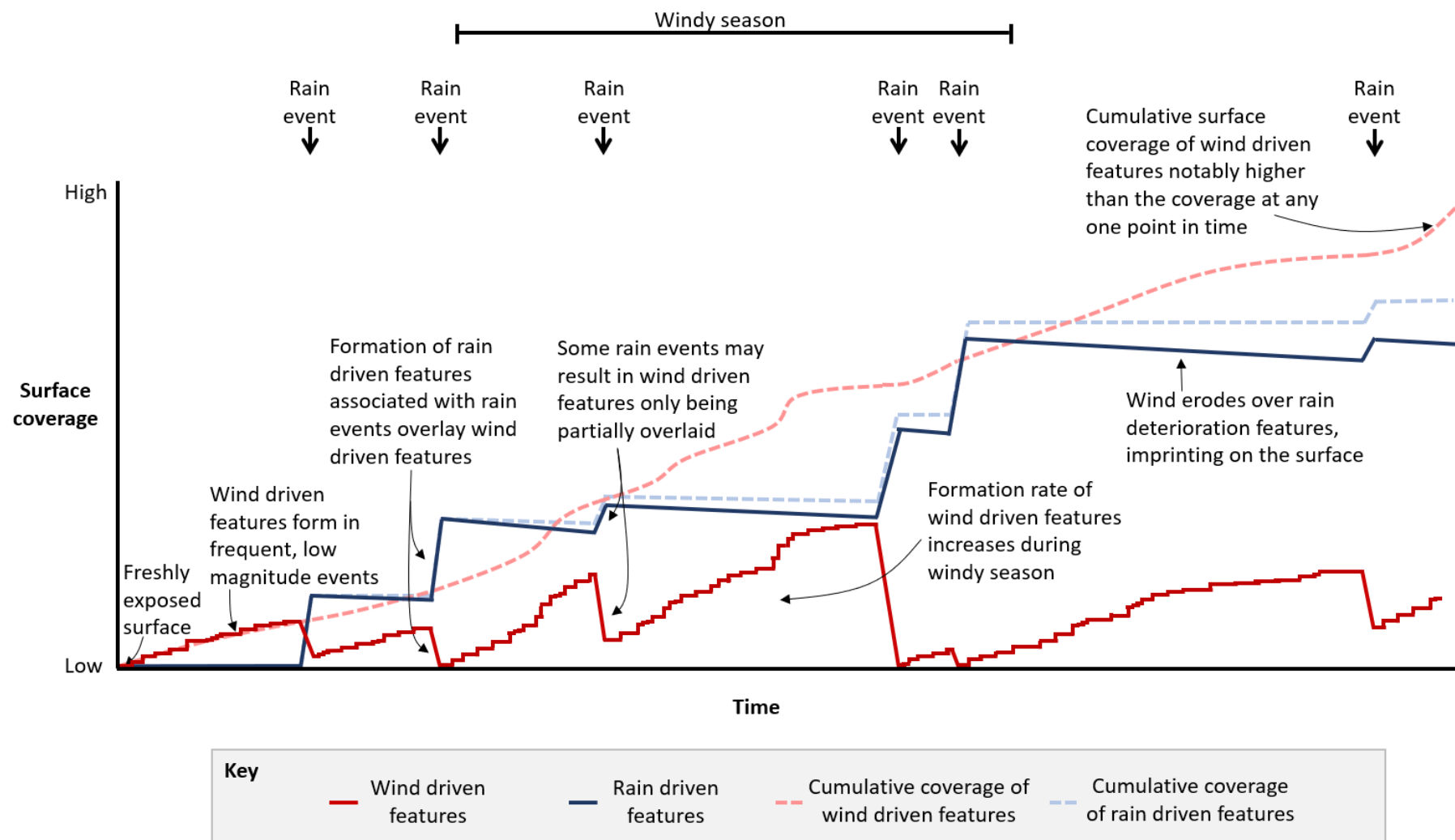


Figure 5.7: A schematic of the surface coverage of wind- and rain-driven features over time. The cumulative impact of these features is shown with a dotted line.

This suggests that in semi-arid to arid environments, a greater emphasis is needed on investigating wind as a driver of earthen heritage deterioration. This finding could present an opportunity for earthen heritage conservation as it suggests that low-cost nature-based strategies such as windbreaks could be effective strategies to minimise future deterioration (Richards et al., 2020). Further research is needed to test the efficacy of such conservation strategies at reducing deterioration at earthen heritage sites.

5.5 Conclusion

Many earthen heritage sites located in dryland environments are experiencing extensive deterioration. This study combined approaches from geomorphology with understandings from heritage science to investigate the relative importance of wind and rain in driving earthen heritage deterioration. Findings from this study highlight the importance of wind as an initiator of earthen heritage deterioration, and, as a driver that can cause extensive deterioration on walls exposed to the prevailing wind.

The importance of wind is likely to have been previously overlooked due to: (i) the low magnitude of individual wind events, (ii) the small volume of material loss associated with wind-driven deterioration and (iii) the low persistence of wind-driven deterioration features. However, the cumulative effect of wind events results in wind being a vital driver of earthen heritage deterioration - with large-scale deterioration features located on walls exposed to the prevailing winds.

The outcomes from this study present an opportunity for earthen heritage conservation strategies to investigate the potential strategies that minimise wind speed at earthen

heritage sites. Future research should investigate how strategies such as windbreaks could minimise future earthen deterioration.

5.6 Chapter 5: Summary and implications

The geomorphological signatures present on test and historic walls at Suoyang show that the types and severity of deterioration features vary with exposure to weather events. Rain-driven deterioration features are associated with the loss of larger volumes of material and have higher persistence than wind-driven deterioration features. However, the high frequency of wind events, despite being of low magnitude, result in wind having an important cumulative impact on deterioration. Wind has also been and continues to be an important initiator of deterioration at Suoyang.

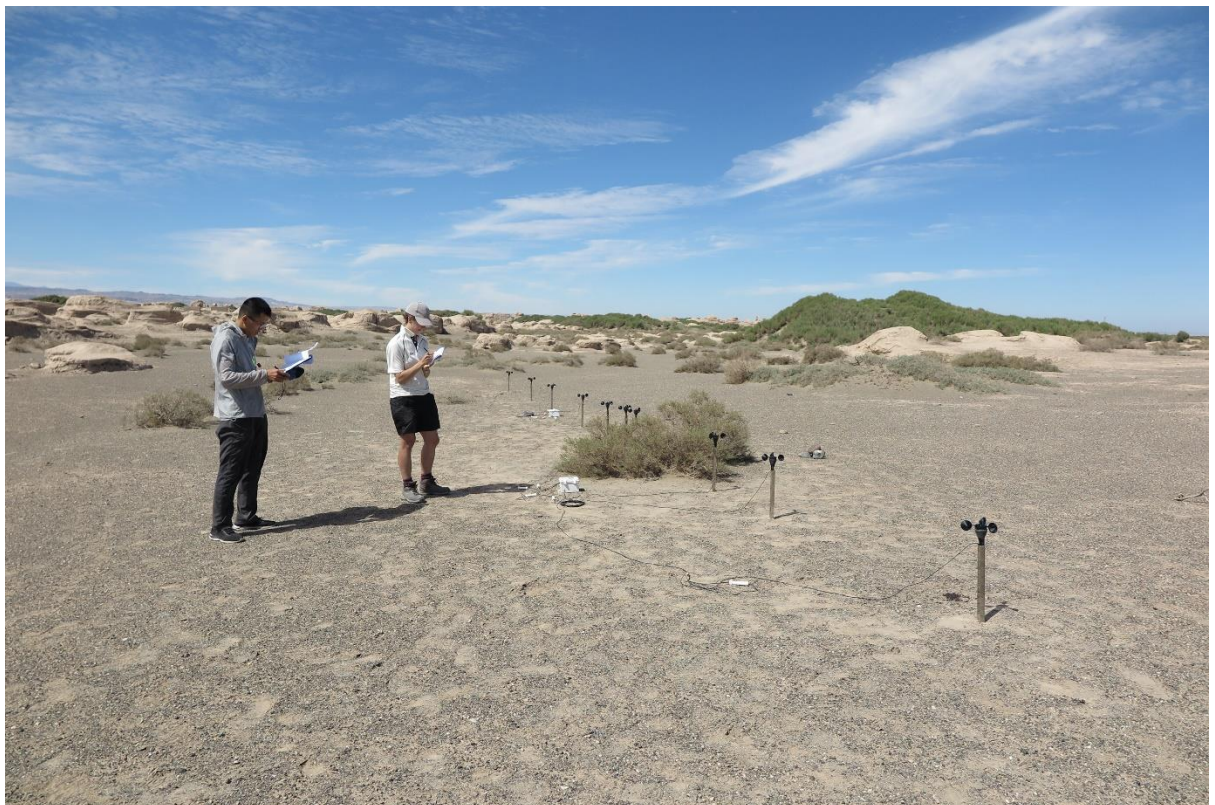
To most effectively minimise further deterioration at earthen heritage sites, we need to understand how these environmental drivers are likely to cause deterioration in the future, and be able to test the effectiveness of potential conservation strategies.

To achieve this, we need a tool that:

- (i) captures complex interactions and feedbacks between future environmental processes and the resultant deterioration; and
- (ii) is able to simulate a range of conservation strategies that could be implemented at earthen heritage sites.

Section 3

Earthen heritage deterioration under future conservation and climatic scenarios



Section 3: Overview

Section 3 addresses: objective 3 (Create an analytical framework that combines and evaluates the risk of multiple environmental drivers of deterioration pose to earthen heritage); and objective 4 (Determine the risk posed by environmental drivers of deterioration to earthen heritage under a range of future climate scenarios and conservation strategies), by presenting and applying the Vegetation and Sediment TrAnsport model for Heritage Deterioration (ViSTA-HD).

Chapter 6 (Paper 3) presents and validates ViSTA-HD, a cellular automaton model that assesses the risk of environmentally-driven earthen heritage deterioration, using environmental and deterioration data collected at Suoyang. Chapter 7 (Paper 4) uses ViSTA-HD to determine the risk of earthen heritage deterioration under future conservation and climatic scenarios.

Paper 3 is written for both a modelling audience interested in environmental systems and earthen heritage researchers studying interactions between natural and built systems. Paper 4 is written for a broad scientific audience with an interest in the impacts of climate change on built environments.

6 Modelling the risk of deterioration at earthen heritage sites in drylands (Paper 3)

Published as: Richards, J., Mayaud, J., Zhan, H., Wu, F., Bailey, R. and Viles, H. (2020) Modelling the risk of deterioration at earthen heritage sites in drylands. *Earth Surface Landform Processes*. In press. doi: 10.1002/esp.4887.

Supplementary Information accompanying this paper can be found in Appendix C. References in the following chapter to the sections/figures within Supplementary Information start 'C.'. For example, 'Figure C.1' refers to Figure C.1 in Appendix C.

Abstract

The variable climatic and environmental conditions associated with dryland regions can cause rapid erosion to both natural and human-made earthen structures. Whilst there is a long history of research into the evolution of erosional landforms such as yardangs, little research has investigated how dryland processes influence the erosion of built structures. Earthen heritage sites located in arid and semi-arid environments experience rapid deterioration caused by exposure to environmental drivers such as wind and rain. Understanding how these environmental drivers interact with each other and cause deterioration to earthen material is vital for successful conservation strategies. To address this need, we present the Vegetation and Sediment TrAnsport model for Heritage Deterioration (ViSTA-HD) that simulates the risk of polishing, pitting and slurry on earthen heritage in a spatially specific manner. A technical description of the model is provided and sensitivity and validation tests are reported. The model is then used to simulate the risk of deterioration occurring over centennial timescales at a Suoyang Ancient City, located in semi-arid, northwest China. The modelled risk of deterioration is in good agreement with deterioration patterns found at Suoyang, with the risk of polishing predominantly occurring around the wall edges, areas at risk of pitting echoing the dune formation and the risk of slurry occurring in drape like patterns down the wall face. Consequently, ViSTA-HD is a powerful and versatile model that can be used to help inform our understandings of long-term interactions between dryland processes and deteriorative impact on earthen structures.

Key words: deterioration, earthen heritage, cellular automaton model, northwest China, conservation

6.1 Introduction

Dryland research has a long history of investigating the climatic and environmental processes that cause the development of natural landforms (Bull, 1977; Greeley and Iversen, 1985; Wasson and Hyde, 1983). The development of erosional landforms, such as yardangs, result from complex interactions between environmental conditions and the parent material (Greeley and Iversen, 1985; Gutiérrez-Elorza et al., 2002). For yardangs, erosion is predominately driven by aeolian processes (abrasion and deflation), with non-aeolian processes (gullyng, fluvial processes) influencing the landform's profile (Barchyn and Hugenholtz, 2015; Dong et al., 2012; Laity, 2009). Despite human-made earthen structures in dryland regions being exposed to similar climatic and environmental processes, little research has investigated how dryland processes influence the erosion of earthen structures (Rainer, 2008). These understandings are particularly needed for the hundreds of earthen heritage sites located in dryland regions (WHEAP, 2012), as many are experiencing rapid deterioration due to their low durability to environmental processes (L. Li et al., 2011; Rainer, 2008).

Wind and rain have previously been found to be the major drivers of deterioration at earthen heritage sites (Du et al., 2017; L. Li et al., 2011; Shao et al., 2013; X. D. Wang et al., 2010). High-magnitude, low-frequency wind-driven rain events tend to cause the greatest rate of deterioration, while high-frequency, low-magnitude wind events cause significant deterioration over longer timescales (Richards et al., 2019b; Shao et al., 2013). In contrast to many natural landforms that are left to erode, heritage conservators generally aim to minimise the rate of erosion to enable the site to be passed on to future generation. Heritage experts have expressed a preference for

earthen heritage conservation strategies to operate over centennial timescales (Richards et al., 2018).

Research into earthen heritage deterioration has typically been undertaken over periods of weeks to years, resulting in the complexity of deterioration processes not being captured over longer time periods (Cui et al., 2019; Mao et al., 2015; Richards et al., 2019b). Deterioration studies undertaken in the laboratory or on test walls have been constrained in their experimental sample size and duration (e.g. Mao et al., 2015; Richards et al., 2019b; Taylor, 1990), while field research has been hindered by gaps in (or complete lack of) environmental records for a site. This often results in the classic geomorphological issue of equifinality – where two different process histories may have feasibly caused the same deterioration feature (Haines-Young and Petch, 1983). Given these challenges, there is an urgent need for a tool that enables us to:

- (i) understand how the predominant drivers of deterioration (wind, rain and sediment) interact with each other around earthen heritage sites, and what impact these drivers have on the risk of deterioration over a centennial timescale.
- (ii) test the effectiveness of potential conservation strategies over centennial timescales.
- (iii) investigate how future changes to climate may impact the risk of deterioration at earthen heritage sites and test the effectiveness of potential conservation strategies under such climate changes.

Modelling allows us to answer these questions due to models' ability to resolve complex processes in dryland environments over multiple spatial and temporal scales (Lesschen et al., 2009; Merritt et al., 2003; Young et al., 2006). Models have commonly been used within geomorphology to investigate interactions and feedbacks between environmental processes (Bagnold, 1941; Laity, 2009; Schumm and Lichty, 1965), but modelling has only rarely been applied to investigate earthen materials and deterioration processes (Bui et al., 2016; Luo et al., 2019; Nowamooz & Chazallon, 2011; Peng et al., 2015). Furthermore, the development of an enviro-heritage model would enable the deterioration risk to be assessed without the need for regular site visits, which, particularly for remote sites, can be expensive and time consuming.

However, modelling interactions between earthen heritage and the environment over a landscape scale can often be computationally expensive. One class of model that has been successfully applied at a landscape scale, partly owing to its computational efficiency, is the cellular automaton model (CA) (Mayaud et al., 2017a; Nield & Baas, 2008a). CAs are numerical models based on grid cells that interact with one another through local rules, and have been used to model environmental processes from dunefield evolution (Baas & Nield, 2010; Mayaud et al., 2017a; Nield & Baas, 2008a, 2008b) to dryland vegetation change (Bailey, 2010; Dunkerley, 1997; He et al., 2005; Vega and Montaña, 2011).

CA models have been widely applied to simulate processes along the horizontal plane (e.g. Dunkerley, 1997; Kerner et al., 2002; Nield and Baas, 2008a), but vertical-plane processes, such as the deterioration of wall faces, have rarely been investigated using CAs. This is partly a result of vertical-plane processes being generally undertaken over

scales small enough to apply computationally expensive models, which are able to capture the complex stresses and strains within vertical materials (Allen, 2019; Ciantia and Castellanza, 2016; K. Zhang et al., 2016). However, such computationally expensive solutions cannot be applied to earthen sites, where walls regularly span hundreds of meters.

Given the issues around computational expensiveness of existing vertical models, and the proven ability for CAs to resolve environmental processes horizontally, this paper aims to:

- i) present a CA model that combines a horizontal environmental module with a vertical module that determines the risk of deterioration across a wall face.
- ii) verify and validate the model performance using data collected from an earth heritage site.

We use the Vegetation and Sand TrAnsport model (ViSTA), originally designed to investigate sand dune reactivation in the Kalahari (Mayaud et al., 2017a, 2017b), as a basis for developing the new Vegetation and Sand TrAnsport model for Heritage Deterioration (ViSTA-HD). We combine dryland geomorphological concepts with data collected at the earthen heritage site of Suoyang Ancient City (northwest China) to build deterioration risk functions into ViSTA-HD. We present a range of sensitivity and validation exercises to ensure the reliability and accuracy of our model.

The ViSTA-HD model we present here is a first attempt at testing the feasibility of coupling environmental processes with deterioration risk of earthen heritage. ViSTA-HD

has been designed as a tool to inform conservation strategies over decadal to century timescales, allowing users to evaluate potential consequences of climate change for earthen heritage. Although the present form of ViSTA-HD is based on environmental and deterioration data from a specific earthen heritage site, its functional versatility allows it to be adapted and applied to other earthen sites in dryland environments around the world.

6.2 Data collection

The behaviour of the model is driven by forcing conditions (e.g. initial windspeed) and parameters used to represent various physical processes. As processes are not resolved explicitly, we use parameterizations to account for the effects of the processes, chosen with the aid of empirical data. We first report on a series of *in-situ* experiments designed to provide such data. We collected data on environmental conditions that can cause deterioration to earthen material (e.g. wind velocity, wind flow round vegetation and sediment transport), as well as on the type and extent of deterioration features present on earthen heritage.

6.2.1 Field site

Field experiments were undertaken at Suoyang Ancient City (锁阳城), hereafter known as Suoyang, during a two-week fieldwork period in August 2018. Suoyang is located in the semi-arid area of Gansu Province, China, and dates back to the Han (206 BC–220 AD) and Tang (618 – 907 AD) dynasties (UNESCO, 2014). It is an archaeological site built out of rammed earth that was abandoned ~400 years ago (Xie et al., 2007a). The site was enlisted as part of the Silk Roads World Heritage Site in 2014 and exhibits a variety of

deterioration features caused by wind, sediment transport and rain (Richards et al., 2019b). This has resulted in pitting, polishing and slurries occurring on the wall faces as well as the formation of larger features on the earthen walls such as cracks, gullies, slumps and collapses (Figure 6.1).

Suoyang's remote location and harsh continental climate mean that it has remained understudied until recently. Since 2015, an experimental test area has been constructed at the site, including a set of four large test walls each measuring 3 m long, 2 m high and 1 m wide. As a result, the site of Suoyang now provides a unique opportunity to investigate environmental and deteriorative processes representative of many other remote sites in this climatic region (e.g. Li et al., 2011; Wang et al., 2010a).

6.2.2 *Wind*

Wind flow was measured around one of the four test walls at Suoyang. A transect of cup anemometers (height 0.5 m) was set up perpendicular to the test walls (similar to the setup of Mayaud et al., 2016a), with anemometers located at distances of 0.5 h , 3 h , 5 h , 10 h and 20 h (where h is the wall height) upwind and downwind of the wall (Figure 6.2a). Two additional anemometers were placed on each side of the wall (one between the two walls and the other on the open side of one of the walls). Wind velocity was recorded every minute for 7 days. Measurements were filtered according to the approaching wind direction, and average wind velocities were normalised to measurements at 20 h upwind (Van Boxel et al., 2004).

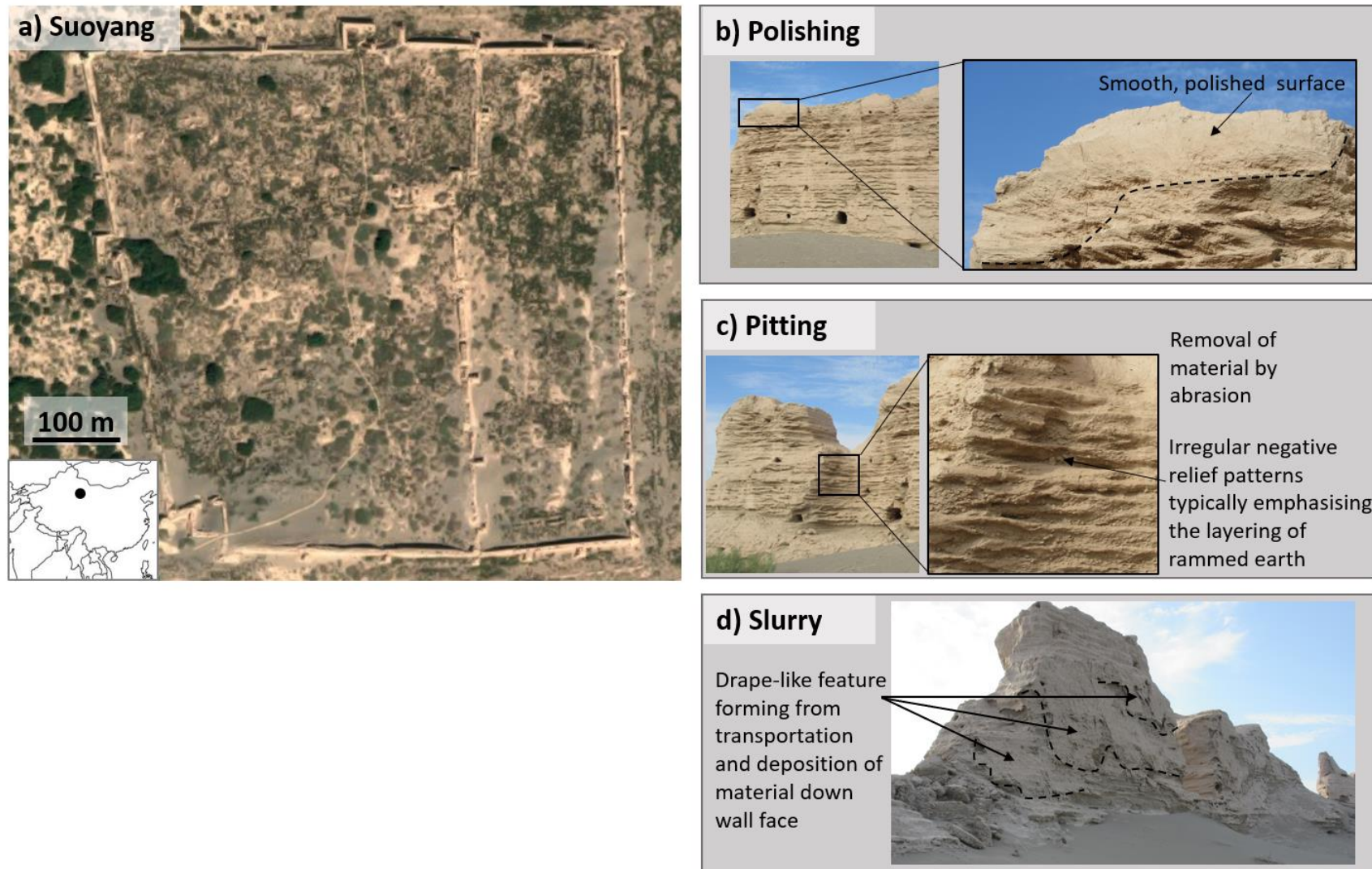


Figure 6.1: Suoyang Ancient City. a) An aerial view showing the layout of the inner city walls with location of Suoyang in China inset (Credit: Google Earth) and the deterioration features found the site of a) polishing, b) pitting and d) slurry.

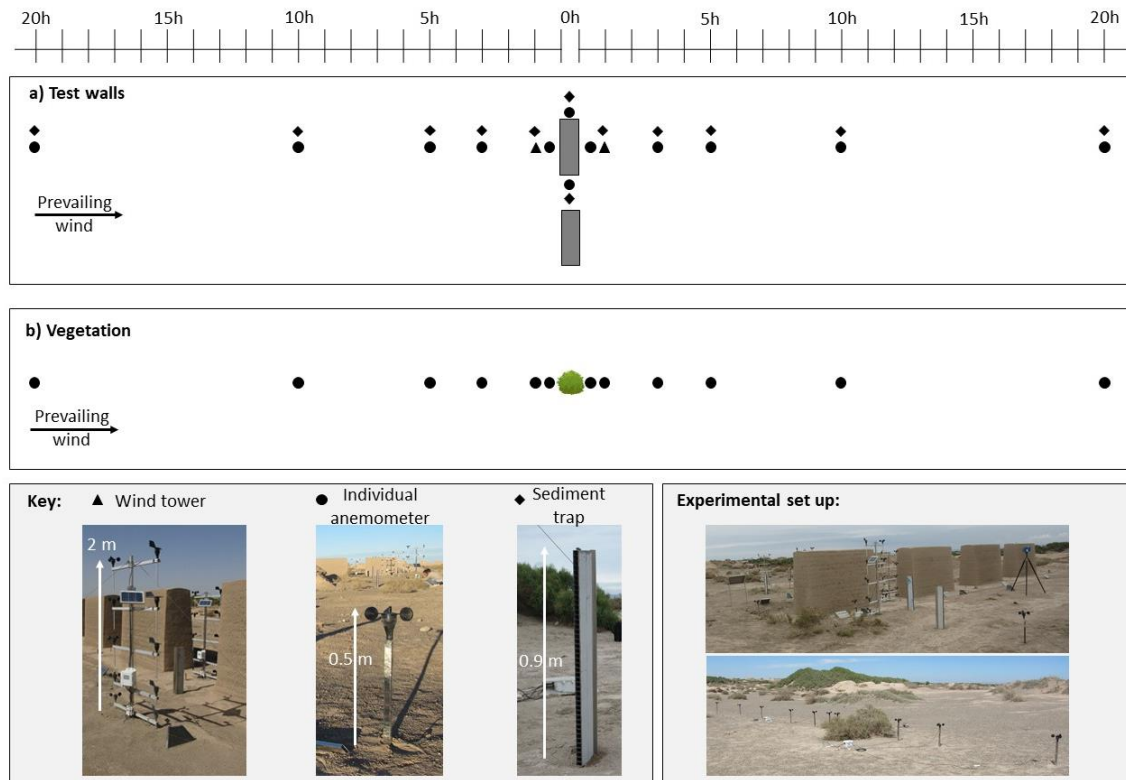


Figure 6.2: Plan view of a) the test walls and b) the vegetation transects where h is the height of the element. Along the transects, measurements were taken using individual anemometers (circle), wind towers (triangle) and sediment traps (diamond). Photos of the equipment used and the experimental set up are presented in the bottom panel.

Two wind towers with anemometers 0.2 m, 0.5 m, 1 m, 1.5 m and 2 m above the ground were placed at $1 h$ either side of the test wall (Figure 6.2a; Tsoar, 1983). Measurements were taken every minute for 18 days and filtered according to the approaching wind direction (Van Boxel et al., 2004).

To capture the turbulent nature of wind flow around the walls, flares loaded with theatrical smoke were deployed upwind of the test walls when the prevailing wind was perpendicular to the test wall (Piscioneri et al., 2019). The flares lasted approximately three minutes. Smoke flow was video-recorded, and stills from the videos used to capture turbulent flow patterns in front and around the wall face (Livingstone, 1986;

Piscioneri et al., 2019). Macro-scale smoke patterns were used to visualise sediment transport pathways around the walls.

6.3 Sediment transport

Two types of sediment traps were deployed for one month between June and July 2018 (Gares et al., 1996). Sediment traps, similar in design to a wedge-shaped sediment trap (0.9 m tall with 45 x 0.02 m increment gaps), were deployed along the same transect as the anemometers facing the prevailing wind direction (Figure 6.2a; Nickling and Mckenna Neuman, 1997). In addition, a circular sediment trap (0.5 m tall) with 16 directional openings (0.02 m wide) was deployed to the east of the site (Greenley et al., 1996). The circular trap was located away from the walls, with a clear fetch in all directions. After one month, the mass of sediment captured was recorded for each 0.02 m section in the wedge-shaped sediment trap and for each directional opening in the circular trap. All samples were subjected to grain size analysis (Arens et al., 2002) using a Winner 2308 Dry Wet Particle Size Analyzer.

To gain a broad-scale understanding of sediment movement around the historic city, we used a laser distance measurer to record the dimensions (height, width and length) of small dunes that had formed against the inner walls of Suoyang.

The sediment data was used to inform the sediment transport within the model space and how the volume of sediment varied with wall height.

6.3.1 *Vegetation*

Vegetation elements in dryland environments impact wind flow patterns in a variety of ways (Mayaud et al., 2016b; Wolfe and Nickling, 1993). The porosity of vegetation is one of the primary factors determining the extent to which vegetation slows down wind in its lee and impacts flow recovery (Mayaud et al., 2016a; Plate, 1971; Torita and Satou, 2007; Wolfe and Nickling, 1993). In this study, optical porosity was determined using a digital photogrammetry method adapted from Mayaud et al. (2017a), where photographs of each vegetation element were converted into greyscale images. Black (plant) and white (open) areas were selected using a visually determined threshold value. The mean optical porosity was equal to the percentage of white pixels.

Initial optical porosity tests showed that the structure of the vegetation at Suoyang was similar to vegetation in other semi-arid areas (e.g. in the Kalahari; Mayaud et al., 2017a), although some vegetation elements were notably denser. Vegetation elements at Suoyang with similar porosities to those studied by Mayaud et al. (2016a) were assumed to have the same impact on wind flow. However, to test the impact of higher density vegetation on wind velocity, wind velocity was measured around five high density vegetation elements (with porosities ranging from 2 to 23%) using cup anemometers deployed in the same manner as around the test walls (Figure 6.2b; Mayaud et al., 2016a). Wind measurements were taken by each cup anemometer every 30 seconds for between 40 – 50 minutes for each vegetation element to ensure a sufficient sampling period was captured after the measurements were filtered according to the approaching wind direction (Van Boxel et al., 2004). Filtered average wind velocities were normalised to measurements at 20 *h* upwind (Mayaud et al., 2016a; Richards & Hoxey, 2012).

Vegetation change at Suoyang was assessed using image analysis (Alves et al., 2003; Duguay et al., 2014; E et al., 2007; Rehman et al., 2019). Satellite images from 2006 and 2010 were compared to drone photos taken of the site in 2018. Vegetation was manually identified and determined as a percentage of the total area by digitally calculating the ratio of white pixels (no vegetation) to black pixels (vegetation) (Kenney, 1987).

Vegetation data were used to inform the wind recovery distances around vegetation elements within the model, and whether vegetation coverage should remain static in the model runs reported below.

6.3.2 Average climatic conditions

Average wind velocity was recorded every ten minutes by an automatic weather station at Suoyang intermittently between 2015 and 2018 (Richards et al., 2019b). Wind measurements taken between September 2015 and August 2016 were used to construct probability density functions which, for each model iteration, provide wind velocity values for wind entering the model domain, and then as a reference throughout the domain during calculation of wind flow interruption (Figure C.6).

Rainfall data collected by the automatic weather station between March and December 2018 were used in conjunction with historical climate data for the area provided by the Dunhuang Academy (unpublished) to inform the rainfall parameters in ViSTA-HD (Figure C7).

6.3.3 *Deterioration data*

A semi-quantitative deterioration assessment was undertaken at Suoyang, which included both the type and extent of deterioration present on the earthen walls (Turkington et al., 2003; Zhao et al., 1994). Fifteen survey sites were selected around the inner-city wall to capture deterioration across the site and in a range of micro-climates (e.g. on both highly exposed and sheltered walls). At each survey site the presence and extent of deterioration including polishing, pitting and slurry was noted (Richards et al., 2019b), and photographs were taken for further desk based analysis (Shao et al., 2013; Viles and Goudie, 2007). Richards et al. (under review) provide more information on the deterioration assessment. Outputs from ViSTA-HD under a range of climatic conditions were compared to the deterioration assessment to test ViSTA-HD's ability to capture the risk of earthen deterioration under multiple different climate scenarios.

6.4 Model Description

ViSTA-HD comprises two modules: i) an environmental module that spatially resolves environmental processes occurring around earthen heritage, and ii) a deterioration module that resolves the risk of deterioration occurring across a wall face (Figure 6.3). For each iteration, ViSTA-HD determines the environmental conditions at the upwind face of the wall. These conditions are inputted to the deterioration module to calculate the deterioration risk. ViSTA-HD is designed to simulate environmental conditions occurring along the upwind wall face, because this zone displays the most severe and complex deterioration patterns at Suoyang (Richards et al., 2019b). For the purposes of this study, we focus on the three most prevalent forms of deterioration at Suoyang – polishing, pitting and slurry (Richards et al., 2019b) – but our versatile modelling

framework allows other environmentally-driven deterioration processes to be added if required.

ViSTA-HD is implemented in the Python® programming language (Python 3.7.0 64 bit). It uses code written by the authors that is openly available from the Oxford University Research Archive (DOI: 10.5287/bodleian:nr86P00jY).

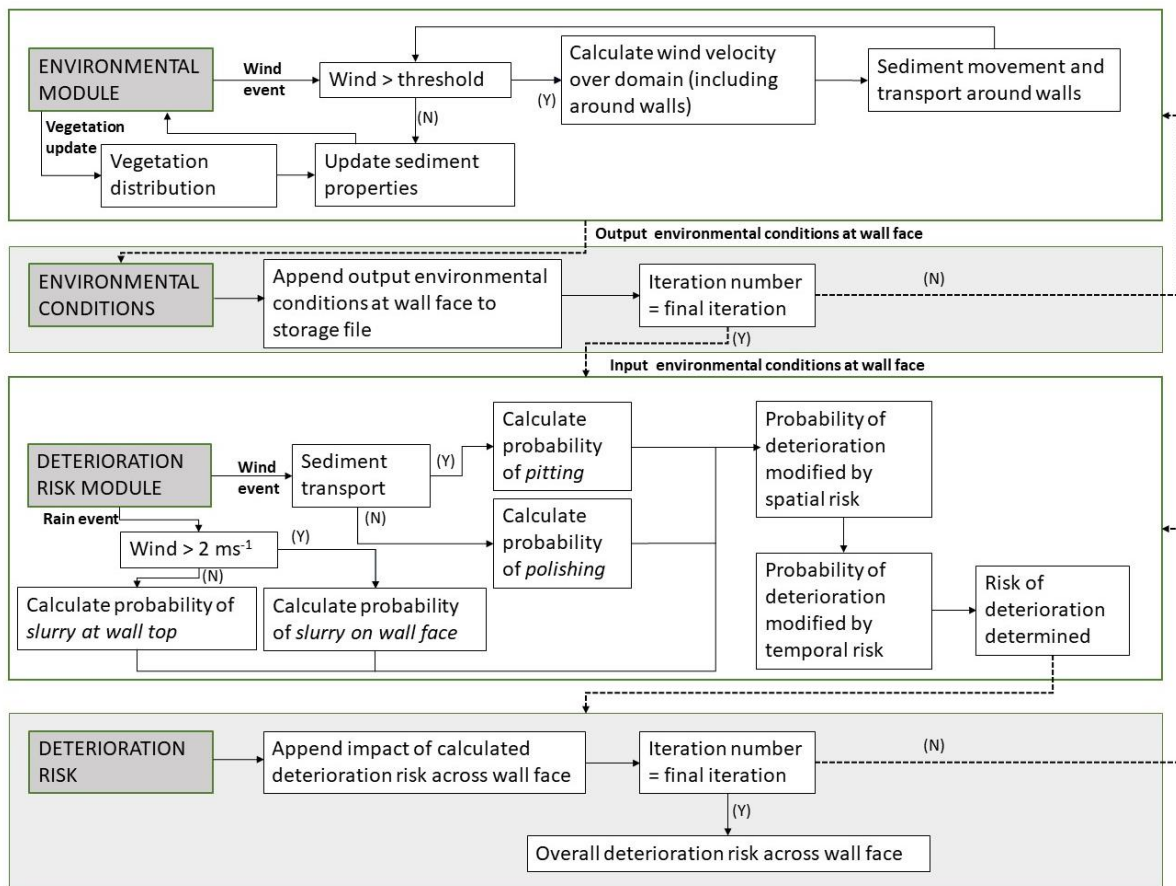


Figure 6.3: A schematic diagram of ViSTA-HD showing the processes occurring in the environmental and deterioration risk modules

6.4.1 Environmental module

The environmental module is based on the ViSTA model (Mayaud et al., 2017a), which was designed to explore vegetation and dune dynamics in the semi-arid Kalahari Desert.

The ViSTA-HD environmental module builds on ViSTA by adding parameterizations of

environmental processes occurring at Suoyang, and including solid earthen walls in the model space. ViSTA-HD's environmental module explicitly resolves wind flow and sediment transport interactions with elements such as vegetation and earthen walls across a horizontal model domain comprised of uniform grid cells. In this paper, we outline the relevant functions that have been adapted for the new ViSTA-HD model; see Mayaud et al. (2017a) for a detailed description of the original ViSTA model.

6.4.1.1 Vegetation

The wind flow in the lee of elements was parameterised in ViSTA as:

$$u_{surf} = (u_{ref} - u_0) \cdot \left(1 - e^{-b \frac{x}{h}}\right) + u_0 \quad (6.1)$$

where u_{surf} is the surface wind velocity (m s^{-1}) at a given distance downwind (x meters) of u_{ref} , an undisturbed reference flow. u_0 is the mean normalised minimum wind velocity at $1 h$ in the lee of the element, $\frac{x}{h}$ is the normalised distance downwind from the element and b is the fitted recovery distance (Mayaud et al., 2017a). As u_0 and b were derived from experimental data and are dependent on porosity, we parameterise them in this study using a combination of datasets from Suoyang and Mayaud et al. (2017a) (see Figure C2). The mean normalised minimum wind velocity (u_0) was parameterised as:

$$u_0 = 0.0002p^2 - 0.0117p + 0.3345 \quad (6.2)$$

where p is the porosity of the vegetation element. The rate of wind velocity recovery behind a vegetation element (b) is parameterised using a threshold relationship where:

$$b = \begin{cases} 0.32 & (p < 65\%) \\ 0.65 & (p \geq 65\%) \end{cases} \quad (6.3)$$

Field studies have found small increases in wind speed around the edges of vegetation elements (Mayaud et al., 2016b). However, given the limited magnitude of the acceleration and the small width of the acceleration zone around the plant compared to the model resolution, acceleration edge effects around vegetation elements have not been included in this version. See Appendix C, Section C.1.1.2 for further information.

6.4.1.2 Solid walls

Wind velocity measurements taken around the test walls showed that wind velocity decelerates from roughly $3h$ upwind of the wall (where h is the height of the wall) owing to the formation of a turbulent zone in front of the wall (Tsoar, 1983). Wind velocity accelerated around the edge of the walls, and the magnitude of acceleration was greater in the gap between two test walls (Baskaran and Kashef, 1996; Blocken and Carmeliet, 2004a).

Based on our experimental data, the acceleration up to 1 m around the edge of the wall (W_{edge}) is parameterised in the model as:

$$W_{edge} = W_{-1h} F_{accel}$$

(6.4)

where W_{-1h} is the windspeed at 1 h upwind of the test wall and F_{accel} is the factor of acceleration, determined by:

$$F_{accel}(\theta) = \begin{cases} -0.0086\theta + 1.7163 & (\text{gap between walls} > 5 \text{ m}) \\ -0.0397\theta + 2.4066 & (\text{gap between walls} \leq 5 \text{ m}) \end{cases}$$

(6.5)

where θ is the wind direction in degrees from perpendicular from the wall face (Figure C3).

In the lee of the test walls, wind recovery is determined using the same parameterization as applied to vegetation (i.e. the wall is considered to be an element with 0% porosity). Research on valleys has shown that incidence angle can impact wind recovery distances (Garvey et al., 2005; Wiggs et al., 2002), but given the small scale of walls, we keep the recovery distance constant following Mayaud et al. (2017a).

The flare experiments and scour markings in front of the walls showed that wind flow interaction with a solid object caused sediment transport pathways to be deflected along the wall face (Figure C4). Therefore, sediment transport pathways in the model are linear unless they intercept with an earthen wall, in which case the pathway gets deflected along the wall face (see Figure 6.4).

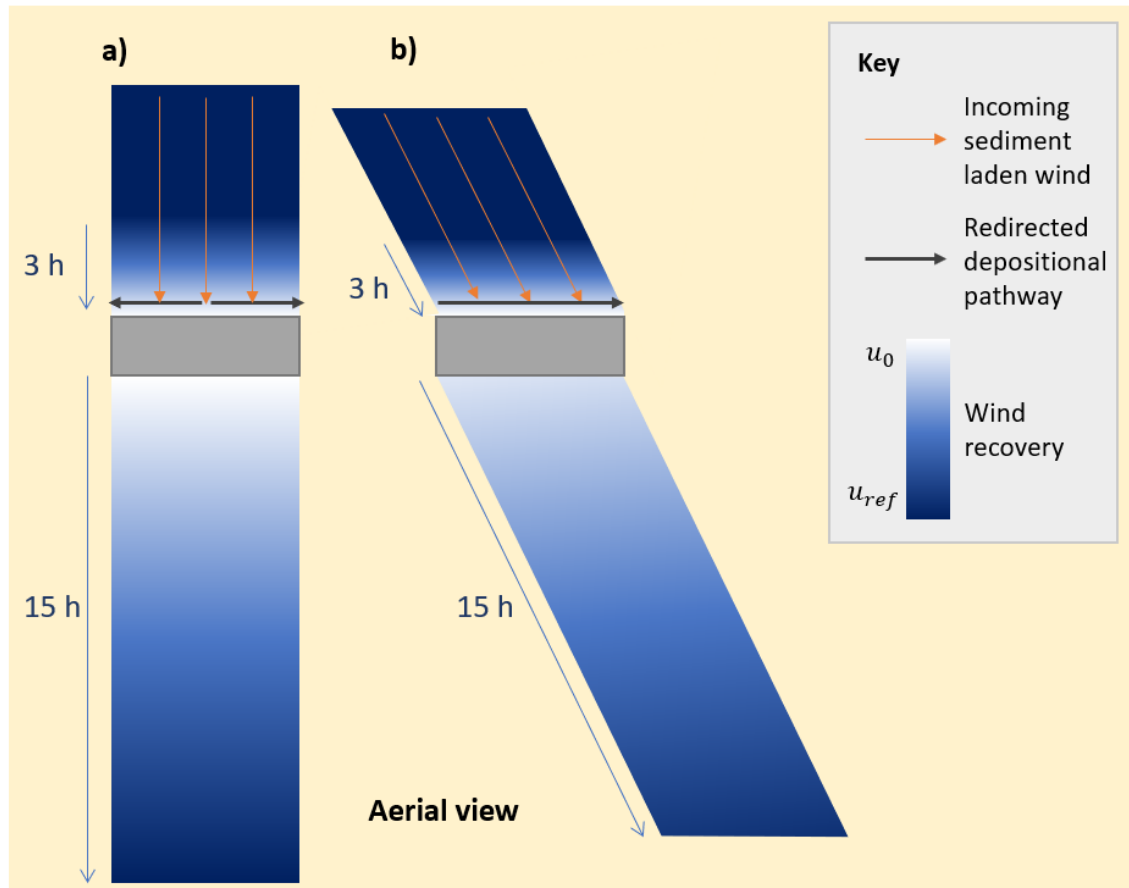


Figure 6.4: The sediment deposition pathway in front of the wall face and the wind velocity recovery in the lee of the wall for a) wind perpendicular to the wall, b) wind at an acute angle to the wall.

6.4.1.3 Temporal scale

ViSTA-HD runs for a number of iterations set by the user. The period of time represented by each iteration, and thus the 'real time' simulated in a run, is dependent on the sediment flux rate, which is also set by the user. To calculate the duration of each iteration, we undertook a verification test comparing the total sediment flux in each modelled iteration to the sediment flux at Suoyang estimated using two techniques: i) calculated using Dong et al.'s (2003) sediment transport model, which quantifies the amount of sediment flux expected from an aeolian system under ideal conditions, and ii) calculated from the mass of sediment collected in the field using a circular sediment trap.

The sediment flux in ViSTA-HD was determined by running the environmental module with environmental and climatic conditions representative of those at Suoyang (Figures C6 and C7). ViSTA-HD was run 10 times for 200 iterations. The median sediment flux per iteration was 589 kg m⁻¹.

Dong et al.'s (2003) model, reformulated by Bailey & Thomas (2014), was used to calculate the total sediment flux using wind speed and sediment particle size data collected at Suoyang as inputs. Sediment flux was determined by:

$$q(u) = \left(c_1 + \frac{c_2 d}{D}\right)^{-1} \left(1 - \frac{v_T}{u}\right)^2 \left(u^3 \frac{p}{g}\right) \quad (6.6)$$

where $q(u)$ is the sediment flux with a wind speed of u (m s⁻¹), c_1 and c_2 are fitted constants, d is the grain size (95 µm), D is the reference grain size (250 µm), g is the acceleration due to gravity, p is the air density and v_T is the velocity for entrainment. The sediment flux per month was determined to be 214 kg m⁻¹. Due to the idealised nature of Dong et al.'s (2003) model, this calculation provides an upper threshold for the monthly sediment flux. The circular sediment trap (with a 2 cm openings) at Suoyang collected 0.79 kg of sediment over a one-month period between June and July 2018. Extrapolating this data to the same spatial scale as ViSTA-HD and Dong et al.'s (2003) model implies a sediment flux of 39.5 kg m⁻¹. As the sediment trap has an estimated efficiency of ~ 30% (Greenley et al., 1996), this provides a lower threshold of 131 kg m⁻¹. Therefore, each iteration is reflective of three to four months of sediment flux at

Suoyang. As climatic conditions at Suoyang follow the meteorological seasons (DJF, MAM, JJA, SON; Figure C1) each iteration was set to represent three months.

6.4.1.4 Process interactions

Feedbacks between rainfall events and sediment entrainment were not included in ViSTA-HD for three reasons. First, Suoyang receives very low precipitation, with an average ~1 mm per month in winter and ~9 mm per month in summer. Second, rainfall events occur infrequently: rain fell on a single day in SON (September - November) 2018, and on 12 days in JJA (June – August) 2018. Third, the surface sediment layer (top 0-10 cm) usually dries within 24 hours after rain events in semi-arid environments (Okin and Gregory, 2016; Ravi et al., 2006). In fact, during our fieldwork, 10 mm of rainfall fell in a 36-hour storm but the surface sediment had totally dried by the following day.

Therefore, the period of inactive sediment transport is considered to be negligible compared to the seasonal scale (3 months) at which the environmental module is run.

Image analysis of vegetation cover at Suoyang revealed very little change in vegetation cover between 2006 and 2018 (range of 52–54% cover). Consequently, rainfall-vegetation feedbacks were also not included in our experiments, and vegetation cover remained constant throughout each model run. Running ViSTA-HD at other earthen heritage sites may require the inclusion of vegetation growth, which is easily ‘turned on’ in the environmental module.

6.4.2 Deterioration module

The authors added the new deterioration module to the modified ViSTA model as a vertical CA that simulates the deterioration risk of polishing, pitting and slurry – the

three major deterioration features seen at Suoyang (Richards et al., 2019b) and other earthen heritage sites in northwest China, such as Jiaohe Ancient City, Xinjiang Province (Shao et al., 2013) and Yumen Fort, Gansu Province (X. Wang et al., 2010). Polishing is caused by the removal of loose grains of material resulting in a smooth surface. Pitting occurs when environmental processes loosen and deflate grains from the parent material resulting in concave pits forming on the surface (Mao et al., 2015) and slurry is caused by the deposition of runoff-borne sediment down the wall face resulting in the formation of a harder crust (Cui et al., 2019).

In each iteration, the probability of polishing, pitting and slurry, occurring in a cell is calculated according to:

- 1) The impact of the environmental drivers in that given cell (environmental risk; Figure 6.5a),
- 2) The risk of deterioration in neighbouring cells (spatial risk; Figure 6.5b),
- 3) The risk of deterioration that previously occurred in the given cell (temporal risk; Figure 6.5c).

The calculated probability is then used to determine the deterioration risk in the given cell (see Section 6.4.2.4).

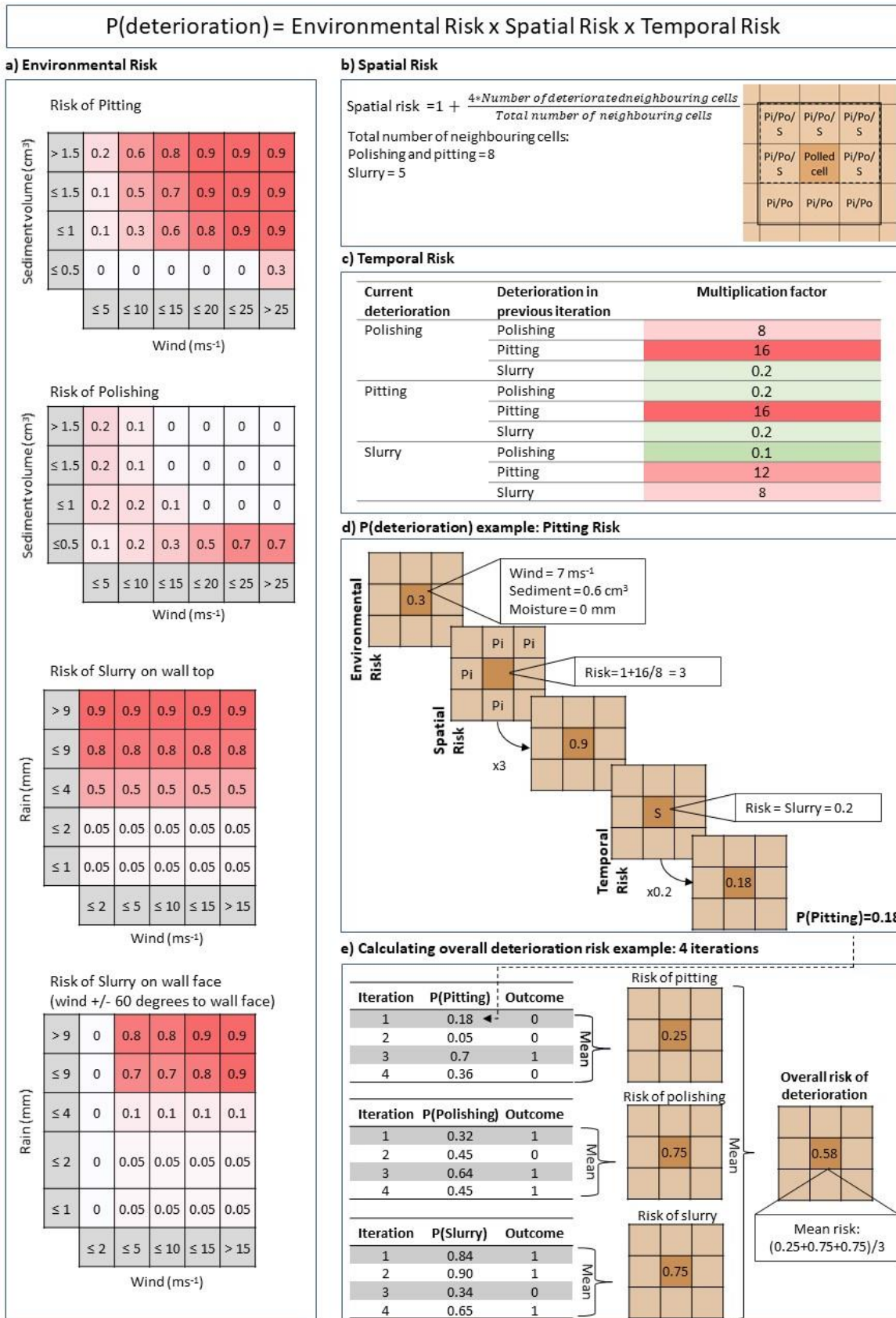


Figure 6.5: The process for determining the overall risk of deterioration given standard a) environmental, b) spatial and c) temporal conditions. Examples of risk calculations are shown in d) and e). The risk of pitting in a polled cell for a single iteration is shown in d) and the overall deterioration given the risks of pitting, polishing and slurry in a polled cell after four iterations is show in e). See section 6.4.2 for how standard conditions were determined. Pi = Pitting, Po = Polishing and S=Slurry.

The cells in the deterioration module are set at a finer spatial resolution than those in the environmental module (0.25 m² and 1 m², respectively), reflecting the difference in scale between processes operating over a landscape compared to processes causing a risk of deterioration across a wall face (Cui et al., 2019; Richards et al., 2019b; Shao et al., 2013).

6.4.2.1 Environmental risk

The environmental risk (E_{risk}) is calculated using risk matrices shown in Figure 6.5a. The environmental risk of polishing and pitting is determined by wind velocity and sediment transport, whereas the environmental risk of slurry is determined by rainfall and wind velocity.

Wind

Wind velocity is resolved at 50 cm above the surface in the environmental module.

Therefore, the wind velocity is inputted to the deterioration module at 50 cm above the surface (Figure C5).

The increase in wind velocity up the wall face was parameterised using the data from the anemometry towers located 1 m upwind of the test walls:

$$W_h = W_{50} \left(3.3576 + \frac{-2.9252654}{1 + \left(\frac{h}{214.6882} \right)^{0.9761477}} \right) \quad (6.7)$$

where W_h is the wind velocity (m s^{-1}) at a given height up the wall, W_{50} is the inputted wind velocity from the environmental module at 50 cm above the surface and h is the height above the surface in centimetres (Figure C6a).

Sediment

All sediment deposited in front of a wall face (as determined by the environmental module) is assumed to have interacted with the wall. Our sediment trap data suggests that the volume of transported sediment decreases with height (Figure C6b), with 67% occurring in the first 40 cm above the surface. This compares well to previous studies, which showed that saltation occurs up to 40 cm above the surface (Dupont et al., 2013). Thus, we set two thirds of the sediment to interact with the wall, within the height limit of the saltation zone.

The volume of sediment that interacts with the wall face is determined by:

$$S_h(h) = \begin{cases} S_{total} \left(\frac{-0.0274h^2 + 2.4323h + 11.281}{100} \right) & (\text{where } h \leq 40 \text{ cm}) \\ \frac{S_{total} - S_{0-40}}{h_{exp} - 40} & (\text{where } h > 40 \text{ cm}) \end{cases} \quad (6.8)$$

where S_h is the volume of sediment hitting the wall surface at a given height (cm), S_{total} is the total volume of sediment deposited in front of the wall per iteration, S_{0-40} is the total volume of sediment that interacted with the wall in the first 40 cm and h_{exp} is the height of the exposed wall above any local accumulation of sand.

Rainfall

The impact of rainfall on earthen heritage is dependent on rainfall volume and wind velocity. Below 2 m s^{-1} , rain is considered as only hitting the wall top in accordance with BS EN ISO 15927-3:2009. At, and above, 2 m s^{-1} , the wind provides enough horizontal momentum for wind-driven rain to occur. Whilst research on buildings has shown that the base of walls are more protected than the tops (Blocken and Carmeliet, 2004b), many earthen heritage structures are shorter than western style buildings and do not have typical building attributes, such as roofs, which affect the intensity of wind-driven rain across a wall. Furthermore, surveys of earthen heritage after storm events have shown moisture impacts across the entire wall face (Appendix C, Section C2.2). Therefore, wind driven rain is modelled as evenly affecting the wall face.

6.4.2.2 Spatial risk

The spatial risk of deterioration captures spatial vulnerability to deterioration. As the material properties of the earthen wall (e.g. variations in clay content, grain size etc.) are not explicitly determined in this model, the spatial risk captures the principle that if neighbouring cells are deteriorated, a given cell is more likely to be vulnerable to deterioration. It is modelled as a linear function:

$$S_{risk}(det) = 1 + \frac{X \cdot Nc_{det}}{Nc_{total}}$$

$$Nc_{total} \begin{cases} 8, & det = pitting, polishing \\ 5, & det = slurry \end{cases}$$

(6.9)

where S_{risk} is the spatial risk, det is the type of deterioration, X is a scaling factor, $N_{c_{det}}$ is the number of deteriorated neighbouring cells and $N_{c_{total}}$ is the total number of neighbouring cells. For polishing and pitting, neighbouring cells are considered to be one cell on each side of the polled cell (including diagonals, Figure 6.5b). For slurry, neighbouring cells are considered to be one cell above and to the side of the polled cell (including the upper diagonals, Figure 6.5b) due to the role of gravity in bringing moisture down the wall face (Y. Zhang et al., 2016).

6.4.2.3 Temporal risk

The temporal risk (T_{risk}) is determined by the deterioration that occurred in the polled cell on the previous iteration. Previous deterioration processes can prime wall surfaces, reducing and enhancing their susceptibility to future deterioration (Figure 6.5c; Cui et al., 2019). The temporal risk values were determined by results from previous studies (e.g. Cui et al., 2019a; Du et al., 2017) and on site visual deterioration assessments at Suoyang. It is modelled as a linear function as shown in Figure 6.5c.

6.4.2.4 Deterioration risk

The risk of pitting, polishing and slurry is separately calculated in each cell by multiplying the environmental, spatial and temporal risks to create three different risk probabilities, $P(det)$, (Figure 6.5d):

$$P(det) = E_{risk} S_{risk} T_{risk}$$

$$det \begin{cases} pitting \\ polishing \\ slurry \end{cases}$$

(6.10)

The cell is then assigned a value of either 0 or 1 based on:

$r = \text{random number between 0 and 1}$

$$\text{cell value} = \begin{cases} 1 & r \leq P(\text{det}) \\ 0 & r > P(\text{det}) \end{cases}$$

(6.11)

In each cell, for each deterioration type, these binary outcomes are collated and averaged over all model iterations (n):

$$\text{Risk}(\text{deterioration}) = \frac{\sum_{i=1}^n P(\text{deterioration})}{n}$$

$$\text{deterioration} \begin{cases} \text{pitting} \\ \text{polishing} \\ \text{slurry} \end{cases}$$

(6.12)

resulting in each cell having a value between zero and one, representing very low and very high risk of deterioration, respectively (Figure 6.5). Values between 0-0.2 and 0.2-0.5 indicate areas of low and medium risk, respectively, while values above 0.5 indicate areas of high risk.

The overall risk of deterioration for each cell is calculated by averaging the risk of deterioration of each of the three deterioration features:

$$Overall\ risk = \frac{Risk(pitting) + Risk(polishing) + Risk(slurry)}{3}$$

(6.13)

The authors would like to strongly emphasise that a value of ‘1’ *does not* mean that deterioration will definitely occur and ‘0’ *does not* mean that deterioration will definitely not occur. These values are merely designed to give an indication of relative risk. For the purposes of this study, we consider the risk of deterioration as the potential for deterioration to occur in a specific special area – not the severity of material loss.

6.5 Sensitivity testing of ViSTA-HD

We present the results from the sensitivity testing undertaken on ViSTA-HD. Additional model verification tests to show that the assumptions and parameterizations used when building ViSTA-HD are suitable for the purpose of investigating earthen heritage deterioration are presented in Appendix C, Section C.2. Further verification tests of the environmental module can be found in the Supporting Information of Mayaud et al. (2017a). In all sensitivity tests, to balance computational expense with capturing smaller scale deterioration features a resolution of 0.25 m² was chosen for the deterioration module (Appendix C, Section C.2.2.3).

The sensitivity of the deterioration module was tested by varying the magnitude of the environmental, spatial and temporal risks (Figure 6.6). All combinations of environmental, spatial and temporal risk scenarios were cross-tested, resulting in 27 outputs (Figure 6.7). Each scenario was run with the same set of starting conditions,

representative of those found at Suoyang, repeated 50 times until the mean and standard deviation had equilibrated (see Appendix C, Sections C.2.1 and C.2.2.2), and then averaged. Zones of the wall face with high levels of agreement across model runs (i.e. standard deviation <5% of the mean risk of deterioration) are hatched, with the variability in deterioration risk generated in Equation (6.11). Areas which are exposed to very high or very low risks of deterioration have the least variability in deterioration risk whilst areas at a medium risk of deterioration have greater variability.

The sensitivity tests resulted in significantly different outcomes when the environmental conditions were run under the uniform scenario (Figure 6.7a) compared to the low (Figure 6.7b) and high scenarios (Figure 6.7c). The uniform scenario resulted in high risk probabilities with equally distributed risk across the wall face, which is unrepresentative of deterioration patterns observed at Suoyang. Both the low and high environmental risk scenarios showed similar patterns of deterioration across the wall face, with the low scenario having a notably lower distribution of deterioration risk (Figure 6.8a). The high deterioration scenario showed greater consensus between model runs and captured a wider range of risks, which were more representative of the deterioration features observed at Suoyang.

There were also notable differences between the results from the spatial and temporal risk scenarios. The 'no impact' spatial and temporal risk scenarios resulted in the lowest deterioration risk, with the high scenarios having the greatest increase in deterioration risk (Figure 6.7a-c). As both spatial and temporal risks are multiplication factors applied to the environmental risk, the impact of the spatial and temporal risk increases with the initial environmental risk. Therefore, if the spatial and temporal scales are set too high,

the scale may become saturated in highly deteriorative environments. This is evident from the peak in the distribution around 1 for high spatial risk (Figure 6.8b). For high temporal scale scenarios, the distribution of mean deterioration risks is more widely spread between 0.75 and 1 indicating that saturation has not occurred (Figure 6.8c).

Given the results from our sensitivity analyses, the standard conditions for the deterioration module are set to those corresponding to a high environmental risk, a low spatial risk and a high temporal risk (Figure 6.5).

Future efforts in the field should be directed at further quantifying the deterioration risk, i.e. more precisely defining what environmental, spatial and temporal conditions lead to specific deterioration features. Such data would enable a quantification of the impact of uncertainty in these parameters on the final model outcomes. In the meantime, we chose parameters for the environmental, spatial and temporal risk that yield sensible outcomes in relation to field conditions. We note that our sensitivity analysis shows that model outcome is not sensitive to these precise values, such that any uncertainty in our final results will not be strongly impacted by uncertainty in these parameters.

a) Environmental Risk

		Uniform						Low						High					
		Sediment (cm ³)	> 1.5	≤ 1.5	≤ 1	≤ 0.5	≤ 5	Sediment (cm ³)	> 1.5	≤ 1.5	≤ 1	≤ 0.5	≤ 5	Sediment (cm ³)	> 1.5	≤ 1.5	≤ 1	≤ 0.5	≤ 5
Risk of Polishing	Wind (ms ⁻¹)	> 1.5	0.5	0.5	0.5	0.5	0.5	> 1.5	0.1	0.3	0.4	0.4	0.4	> 1.5	0.2	0.6	0.8	0.9	0.9
		≤ 1.5	0.5	0.5	0.5	0.5	0.5	≤ 1.5	0.05	0.2	0.3	0.4	0.4	≤ 1.5	0.1	0.5	0.7	0.9	0.9
		≤ 1	0.5	0.5	0.5	0.5	0.5	≤ 1	0.05	0.1	0.3	0.3	0.4	≤ 1	0.1	0.3	0.6	0.8	0.9
		≤ 0.5	0.5	0.5	0.5	0.5	0.5	≤ 0.5	0	0	0	0	0	≤ 0.5	0	0	0	0	0.3
Risk of Pitting	Wind (ms ⁻¹)	> 1.5	0.5	0.5	0.5	0.5	0.5	> 1.5	0.1	0.05	0	0	0	> 1.5	0.2	0.1	0	0	0
		≤ 1.5	0.5	0.5	0.5	0.5	0.5	≤ 1.5	0.1	0.05	0	0	0	≤ 1.5	0.2	0.1	0	0	0
		≤ 1	0.5	0.5	0.5	0.5	0.5	≤ 1	0.1	0.1	0.05	0	0	≤ 1	0.2	0.2	0.1	0	0
		≤ 0.5	0.5	0.5	0.5	0.5	0.5	≤ 0.5	0.05	0.1	0.15	0.2	0.3	≤ 0.5	0.1	0.2	0.3	0.5	0.7
Risk of Slurry on wall top	Wind (ms ⁻¹)	> 9	0.5	0.5	0.5	0.5	0.5	> 9	0.4	0.4	0.4	0.4	0.4	> 9	0.9	0.9	0.9	0.9	0.9
		≤ 9	0.5	0.5	0.5	0.5	0.5	≤ 9	0.3	0.3	0.3	0.3	0.3	≤ 9	0.8	0.8	0.8	0.8	0.8
		≤ 4	0.5	0.5	0.5	0.5	0.5	≤ 4	0.2	0.2	0.2	0.2	0.2	≤ 4	0.5	0.5	0.5	0.5	0.5
		≤ 2	0.5	0.5	0.5	0.5	0.5	≤ 2	0.05	0.05	0.05	0.05	0.05	≤ 2	0.05	0.05	0.05	0.05	0.05
Risk of Slurry on wall face	Wind (ms ⁻¹)	≤ 1	0.5	0.5	0.5	0.5	0.5	≤ 1	0.05	0.05	0.05	0.05	0.05	≤ 1	0.05	0.05	0.05	0.05	0.05
		≤ 2	0.5	0.5	0.5	0.5	0.5	≤ 2	0.05	0.05	0.05	0.05	0.05	≤ 2	0.05	0.05	0.05	0.05	0.05
		≤ 5	0.5	0.5	0.5	0.5	0.5	≤ 5	0.05	0.05	0.05	0.05	0.05	≤ 5	0.05	0.05	0.05	0.05	0.05
		> 15	0.5	0.5	0.5	0.5	0.5	> 15	0.05	0.05	0.05	0.05	0.05	> 15	0.05	0.05	0.05	0.05	0.05

b) Spatial Risk

Multiplication factor	
None	1
Low	$1 + \frac{4 * \text{Number of deteriorated neighbouring cells}}{\text{Total number of neighbouring cells}}$
(Maximum increase = 5x the original risk)	
High	$1 + \frac{16 * \text{Number of deteriorated neighbouring cells}}{\text{Total number of neighbouring cells}}$
(Maximum increase = 17x the original risk)	

c) Temporal Risk

Current deterioration	Deterioration in previous iteration	Multiplication factor		
		None	Low	High
Polishing	Polishing	1	2	8
	Pitting	1	4	16
	Slurry	1	0.5	0.2
Pitting	Polishing	1	0.5	0.2
	Pitting	1	4	16
	Slurry	1	0.5	0.2
Slurry	Polishing	1	0.25	0.1
	Pitting	1	3	12
	Slurry	1	2	8

Figure 6.6: The probabilities used in the sensitivity testing for a) environmental risk scenarios uniform, low and high, b) spatial risk scenarios none (no impact), low and high, and c) temporal risk scenarios none (no impact), low and high

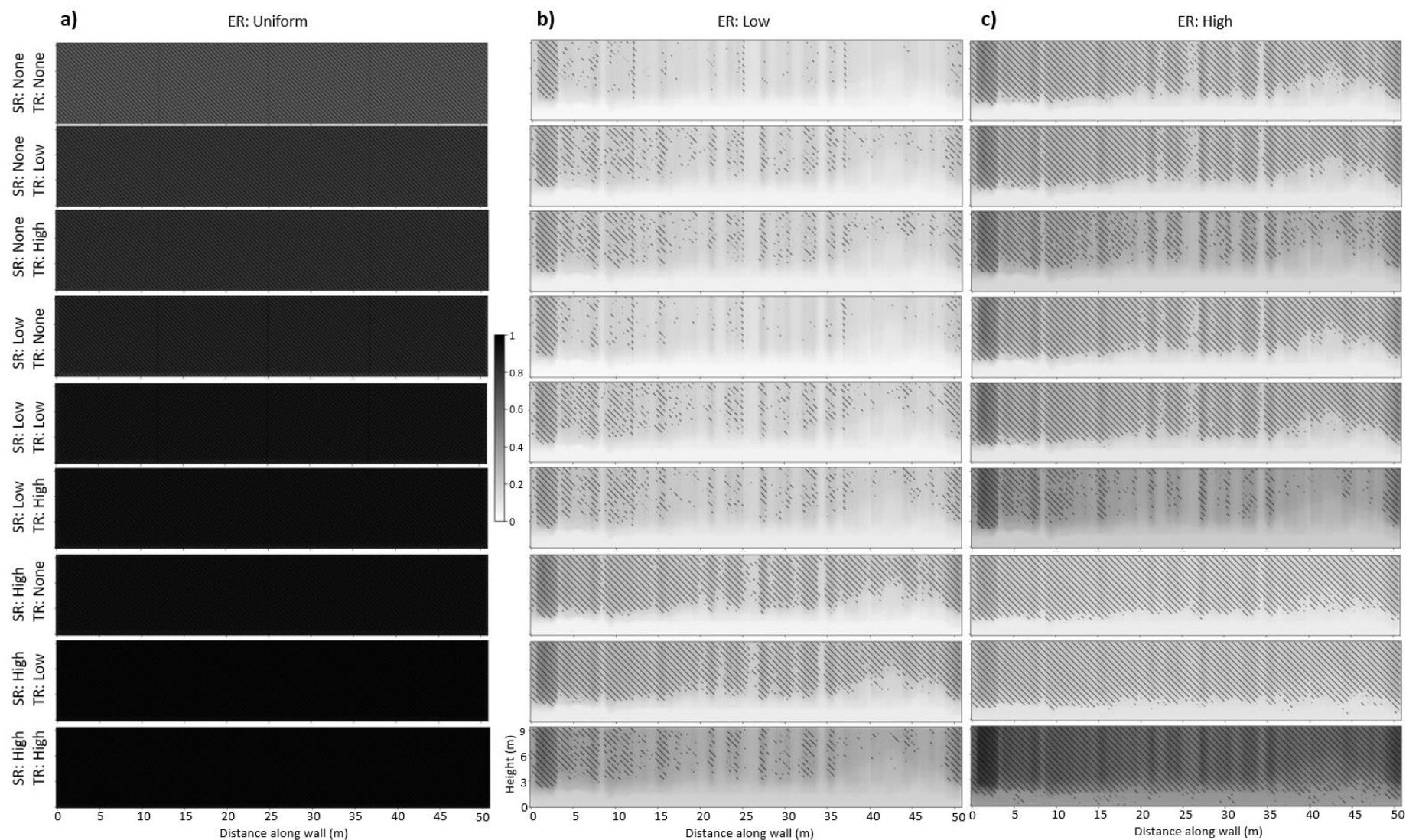


Figure 6.7: The mean risk of deterioration after 50 model runs when inputted a) uniform, b) low and c) high environmental conditions and subjected to varying spatial and temporal risks (ER, SR and TR, respectively – see Figure 6.6 for definitions of uniform, none, low and high). Hatching indicates areas of the wall where the standard deviation is < 5% of the mean. Note the different scales used for ER uniform, compared to ER low and high

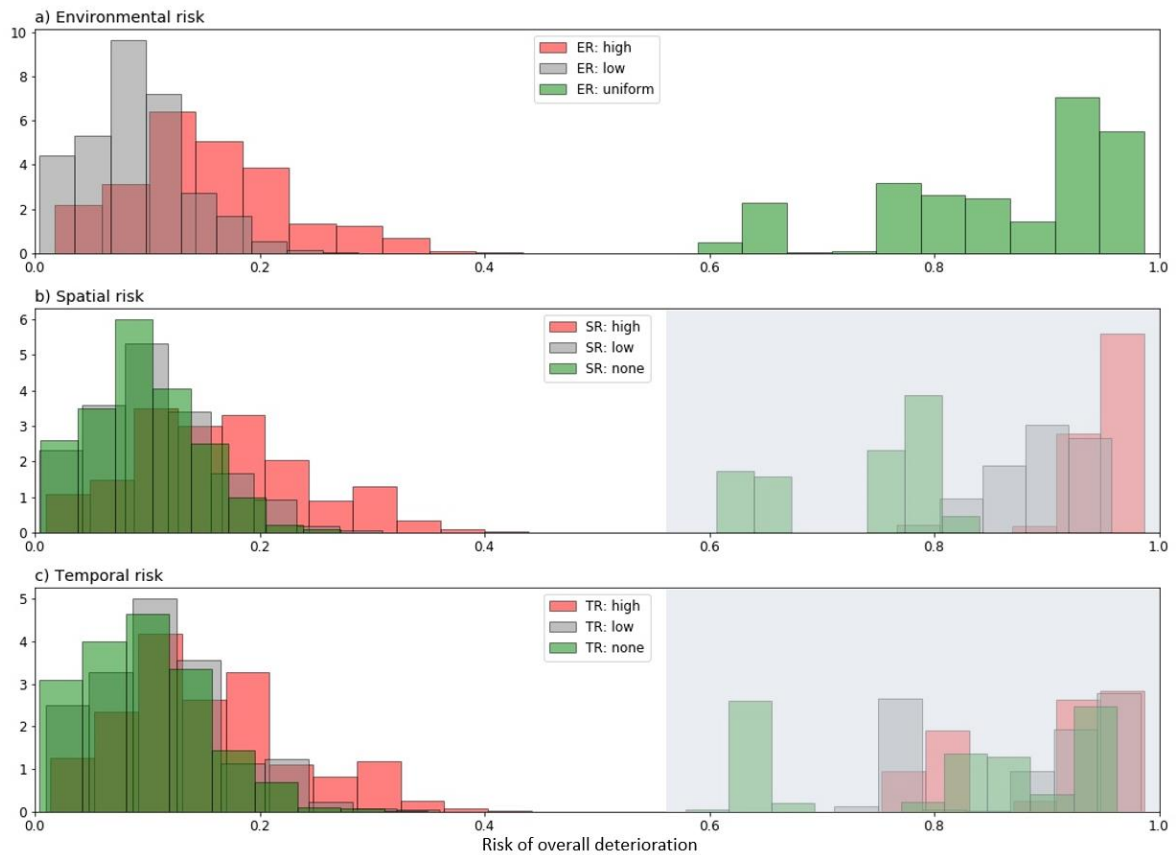


Figure 6.8: The overall deterioration risk in each cell across the wall face for different a) environmental, b) spatial and c) temporal risks (ER, SR and TR, respectively). The areas in b) and c) shaded with grey indicate results from the unrealistic uniform environmental risk scenario and thus should only be considered with regards to saturation of the deterioration risk scale. See text for further discussion.

6.6 Model validation

Deterioration patterns at Suoyang are used to validate (i) the risk of individual deterioration features and; (ii) the overall risk of deterioration under five different environmental conditions occurring on earthen heritage.

6.6.1 Formation of deterioration features

When inputted with environmental conditions representative of those at Suoyang, ViSTA-HD produced deterioration patterns of polishing, pitting and slurry observed at our field site (Figure 6.9). Polishing dominates at wall tops and edges (Figure 6.9b, b-i), pitting follows the development of dunes up the wall face (Figure 6.9c, c-i), and slurry

drapes down the wall face (Figure 6.9d, d-i). In this simulation, given the higher modelled risk of slurry compared to polishing and pitting, slurry patterns dominate in the overall deterioration, except for at the wall edges where polishing plays an important role (Figure 6.9e).

6.6.2 Simulating deterioration in different environments

ViSTA-HD is able to capture the deterioration risk on walls exposed to different micro-climates around Suoyang (Figure 6.10). Five scenarios were tested to simulate areas:

- i) around the on-site weather station exposed to seasonal variations in wind velocity and rainfall;
- ii) sheltered from the prevailing wind and rain;
- iii) exposed to the prevailing wind and sheltered from the rain;
- iv) sheltered from the prevailing wind and exposed to the rain; and
- v) exposed to the prevailing wind and rain.

See Figure 6.10 for definitions of sheltered/exposed wind/rain.

Under conditions similar to weather station records, deterioration was generally evenly distributed across the wall face, with some light drape features forming (Figure 6.10a). This is observed at Suoyang, where many of the walls exhibit some minor deterioration across the wall face with notable features occurring in specific areas such as around weakness or cracks in the material (Figure 6.10a-i).

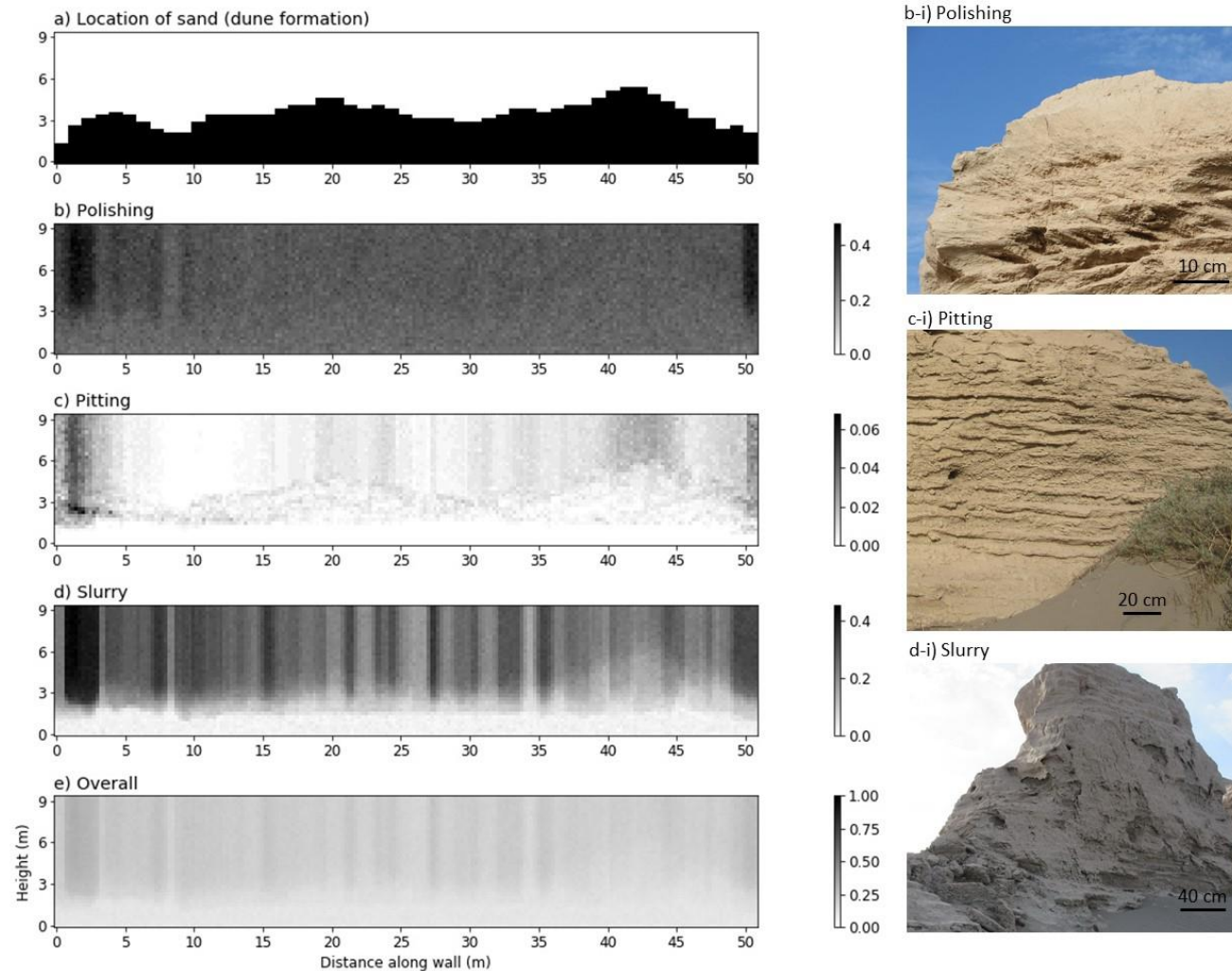


Figure 6.9: a) The maximal height of sand across all model runs ($n=50$) and the mean ($n=50$) risk of b) polishing, c) pitting, d) slurry and e) overall deterioration on a wall face from 50 replicate runs inputted with conditions representative of those at Suoyang. Note the different scales for each deterioration feature; 0= very low risk, 1= very high risk. Examples of b-i) polishing, c-i) pitting and d-i) slurry at Suoyang are shown.

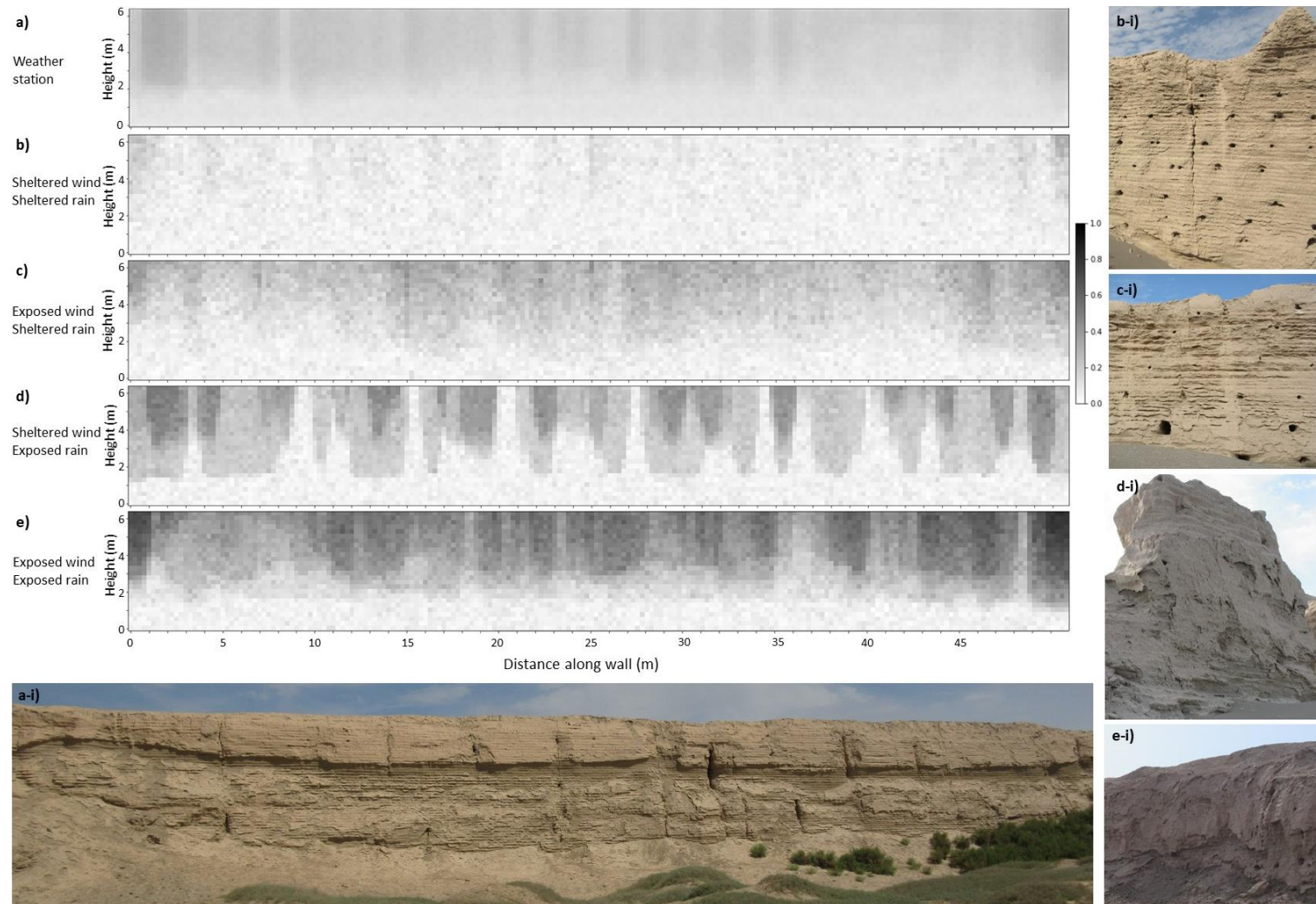


Figure 6.10: Overall risk of deterioration caused by wind and rain a) as determined by conditions recorded by the weather station and for locations b) sheltered from the wind and rain, c) exposed to the wind and sheltered from the rain, d) sheltered from the wind and exposed to the rain and e) exposed to the wind and rain. Photos of deterioration from around Suoyang, representative of the respective conditions modelled are shown (a-i to e-i). Here, sheltered locations are modelled with a mean wind velocity of 5 ms^{-1} and the median rainfall event being 1 mm with an interquartile range of 1.75 mm. Exposed locations modelled with an average wind velocity of 12 ms^{-1} and the median rainfall event being 3 mm with an interquartile range of 8 mm.

Under sheltered wind and rain conditions, there was minimal risk of deterioration except for exposure of the top corners to polishing (Figure 6.10b). With increased wind velocities, the areas at risk of polishing increase but remain predominantly located near the wall tops. This is highly reflective of the deterioration observed on walls sheltered from wind and rain at Suoyang that exhibit small amounts of pitting and polishing along their face (Figure 6.10b-i). Under exposed wind and sheltered rain conditions, the risk of polishing notably increases on the upper half and on the corners of the wall (Figure 6.10c). Whilst most areas at Suoyang exposed to high winds are also exposed to wind-driven rain, polishing and pitting zones occur at the top of walls that are more sheltered from the rain (Figure 6.10c-i).

When subjected to sheltered wind and exposed rainfall conditions, drapes of slurry emerge along the wall face (Figure 6.10d). This pattern corresponds well to thick slurry flows observed in sheltered areas of Suoyang's walls (Figure 6.10d-i). In exposed wind and rain conditions, the impact of wind-driven rain is seen with greater overall risks of deterioration (Figure 6.10e). However, in this case, the drapes of slurry are less distinct than in Figure 6.10d; instead, a more homogeneous sheet of slurry forms across the wall face. This particular feature is seen at Suoyang along walls that are exposed to high wind and rain (Figure 6.10e-i).

6.7 Applications of ViSTA-HD

ViSTA-HD is a robust model that can simulate environmentally-driven deterioration risk across earthen walls. It can simulate a range of deterioration risk patterns representative of the deterioration patterns at Suoyang. ViSTA-HD enables

environmental drivers of deterioration to be assessed over a range of temporal and spatial scales, which is not always feasible in laboratory or field tests. The model also allows practitioners to test the outcomes of different nature-based conservation strategies over decadal and centennial timescales.

ViSTA-HD has the potential to be adapted and applied to other earthen sites in dryland environments, with the addition of site-specific data such as vegetation coverage and sediment flux rates, and the inclusion other environmentally driven deterioration features if prevalent. ViSTA-HD can thus act as a decision-making tool to help conservators and site managers assess trade-offs between possible interventions, enabling a holistic assessment of strategies that are likely to be most effective today and into the future.

ViSTA-HD also acts as a tool for studying the evolution of natural landforms made out of earthen or semi-lithified materials in dryland environments. For example, ViSTA-HD could be adapted to explore the formation of erosional features such as yardangs under present as well past and future environmental conditions (Dong et al., 2012; Ward and Greeley, 1984).

6.8 Conclusion

Understanding the complex interactions between deterioration processes at earthen heritage sites requires tools that explicitly account for temporal and spatial scaling. With this in mind, we developed a new enviro-heritage model, ViSTA-HD, which can spatially resolve the risk of deterioration resulting from wind, sediment transport and rain across

an earthen wall. In its current form, the model produces realistic examples of three forms of deterioration – polishing, pitting and slurry – that arise from exposure to different environmental conditions over space and time. This could be expanded to include other forms of deterioration, if required. Consequently, ViSTA-HD is a powerful and versatile model that can inform understandings of long-term earthen site deterioration and address the research-conservation scale gap currently facing many earthen heritage sites. By reducing the burden on researchers to carry out fieldwork in remote and difficult conditions, models such as ViSTA-HD are invaluable tools for testing the potential outcomes of conservation strategies, and for predicting the likely impacts of future climate and land use change on earthen heritage.

The ViSTA-HD model is now ripe for further testing and validation. In future work, we envisage ViSTA-HD being used to investigate deterioration risk at other earthen heritage sites in semi-arid and arid environments and having the potential to be adapted for understanding the development of natural erosional landforms.

6.9 Chapter 6: Summary and implications

I have developed the Vegetation and Sediment TrAnsport model for Heritage Deterioration (ViSTA-HD) to assess the risk of earthen heritage deterioration for sites located in semi-arid regions. Field data collected at Suoyang was used to parameterise and tune the model. Results showed that ViSTA-HD was able to simulate a variety of deterioration patterns observed on the historic walls at Suoyang.

The ability of ViSTA-HD to simulate realistic patterns of deterioration means it can be used as a tool by researchers and practitioners to investigate:

- (i) how earthen heritage deterioration risk may vary under future climate projections; and
- (ii) the extent to which the implementation of nature-based conservation strategies, such as wind breaks and increasing vegetation cover, minimise the risk of deterioration.

As we continue to increase our understanding of earthen deterioration processes, we should aim to model the *volume* of material loss instead of the *risk* of deterioration. This would enable us to simulate the development of larger deterioration features seen at Suoyang such as turrets.

7 Deterioration risk of dryland earthen heritage sites facing future climatic uncertainty (Paper 4)

Submitted as: Richards, J., Bailey, R., Guo, Q., Mayaud, J., Viles, H. and Wang, X.
Deterioration risk of dryland earthen heritage sites facing future climatic uncertainty.
To *Scientific Reports*.

Supplementary Information accompanying this paper can be found in Appendix D.
References in the following chapter to the sections/figures within Supplementary
Information start 'D.'. For example, 'Figure D.1' refers to Figure D.1 in Appendix D.

Abstract

Uncertainties over future climatic conditions pose significant challenges when selecting appropriate conservation strategies for heritage sites. Choosing effective strategies is especially important for earthen heritage sites located in dryland regions, as many are experiencing rapid environmentally-driven deterioration. We use a newly developed cellular automaton model (ViSTA-HD), to evaluate the environmental deterioration risk, over a 100-year period, under a range of potential climate and conservation scenarios. Results show increased wind velocities could substantially increase the overall deterioration risk, implying the need for wind-reducing conservation strategies. In contrast, predicted increases in rainfall are not likely to increase the overall deterioration risk, despite greater risk of rain-driven deterioration features. Of the four conservation strategies tested in our model, deterioration risk under all climatic scenarios was best reduced by increasing the coverage of natural, randomly-distributed vegetation to 80%. We suggest this approach could be an appropriate long-term conservation strategy for other earthen sites in dryland regions.

7.1 Earthen heritage: a complex conservation problem

Many earthen heritage sites (historic structures formed of earthen materials) are experiencing extensive deterioration that is driven by climatic factors such as wind and rain (Cui et al., 2019a, 2019b; Du et al., 2017; Y. Zhang et al., 2016). For these sites to be passed on to future generations, effective conservation strategies are urgently needed.

Such strategies must:

- (i) address the complexity of interactions between the environment and earthen heritage sites (Cui et al., 2019a; Du et al., 2017; Shao et al., 2013);
- (ii) minimise the risk of environmentally-driven deterioration;
- (iii) have a minimal impact on the value(s) associated with the heritage;
- (iv) are practically feasible to implement and maintain (Richards et al., 2018).

However, uncertainties over future changes in climate (Christensen et al., 2013; Hui et al., 2018; Wang and Chen, 2014) pose significant challenges for selecting appropriate conservation strategies, because they may alter the processes causing environmentally-driven deterioration. There is therefore a pressing need for a research-driven approach to identify effective conservation strategies under both current and potential future climates.

Earthen heritage sites are commonly found in dryland environments, owing to a combination of widespread availability of earthen materials and favourable climatic conditions for their longevity (WHEAP, 2012). In regions along the ancient Silk Road in Asia, rammed earth has been used to form a wide variety of structures, from homes and temples to entire cities (L. Li et al., 2011; Z. Li et al., 2011; Pu et al., 2016a; Richards et al., 2019b). These earthen sites have considerable historic and scientific value, because

of the key role they play in documenting the spread of knowledge, religion and trade between Europe and Asia (Richards et al., 2018; Xie et al., 2007b).

The low durability of earthen sites when exposed to wet, windy conditions (Beckett et al., 2020) means that many earthen sites exhibit extensive deterioration features when they are not effectively conserved (Du et al., 2017; Pu et al., 2016a; Shao et al., 2013; X. D. Wang et al., 2010). Two principal conservation approaches exist to minimise the rate at which the historical material deteriorates: either erodibility-reduction methods, which strengthen material, or erosivity-reduction methods, which reduce the strength of environmental drivers before they interact with a site. In general, many heritage experts express a strong preference for the latter – strategies that modify environmental conditions (Richards et al., 2018). Potential conservation strategies for earthen heritage sites include nature-based solutions, such as windbreaks and greater natural vegetation coverage (G. S. Li et al., 2013; Richards et al., 2018).

In this paper, we present a framework to test the effectiveness of potential conservation strategies for earthen heritage under current and potential future climate scenarios. This framework is designed to empower decision makers to deploy appropriate conservation strategies quickly and efficiently in some of the most fragile sites on the planet.

7.2 Modelling deterioration risk

This paper applies a novel numerical modelling method to evaluate the potential risk of deterioration under future climate and conservation scenarios. We use the Vegetation and Sediment TrAnsport model for Heritage Deterioration (ViSTA-HD), a cellular automaton model developed by the authors that couples environmental and heritage deterioration processes (Richards et al., 2020).

ViSTA-HD simulates environmental conditions around earthen heritage sites in dryland environments and resolves deterioration risk in a spatial manner. This enables us to detect changes across wall faces under different climate and conservation scenarios. Richards et al. (2020) provide a detailed explanation and extensive set of verification and validation tests for ViSTA-HD, with empirical data supporting the model formulation. The Methods section in this paper provides further description of the model.

In this study, we use ViSTA-HD to simulate the risk of deterioration over a 100-year time period at Suoyang Ancient City (锁阳城, hereafter Suoyang), an earthen heritage site located in semi-arid northwest China. Suoyang is an ancient rammed earth city built during the Han (206 BC–220 CE) and Tang (618 – 907 CE) dynasties, and was enlisted as part of the Silk Roads World Heritage site in 2014 (UNESCO, 2014) (Figure 7.1a). Many parts of the site, especially those facing the prevailing easterly wind, have experienced extensive deterioration. On some walls perpendicular to the prevailing wind, dune features have also formed on wall faces both up and down wind (Figure 7.1b, c). Twenty-first century climate projections for northwest China suggest sites, such as Suoyang, are facing future climate uncertainties. CMIP5 (Wang and Chen, 2014; Zhou et al., 2014) and regional climate models (PRECIS - Guo et al., 2018, 2017; RegCM3 - Gao et al., 2012; Jiang et al., 2010; RegCM4 - Hui et al., 2018 and CMM5 - Jiang et al., 2010), show rainfall projections ranging from a 10 % decrease (Christensen et al., 2013; Hui et al., 2018) to 50% increase (Gao et al., 2012; Hui et al., 2018; Wang and Chen, 2014), while wind velocity projections vary from a decrease of 1 ms^{-1} to an increase of 1 ms^{-1} (Jiang et al., 2010; Xiong et al., 2019).

a) Suoyang Ancient City



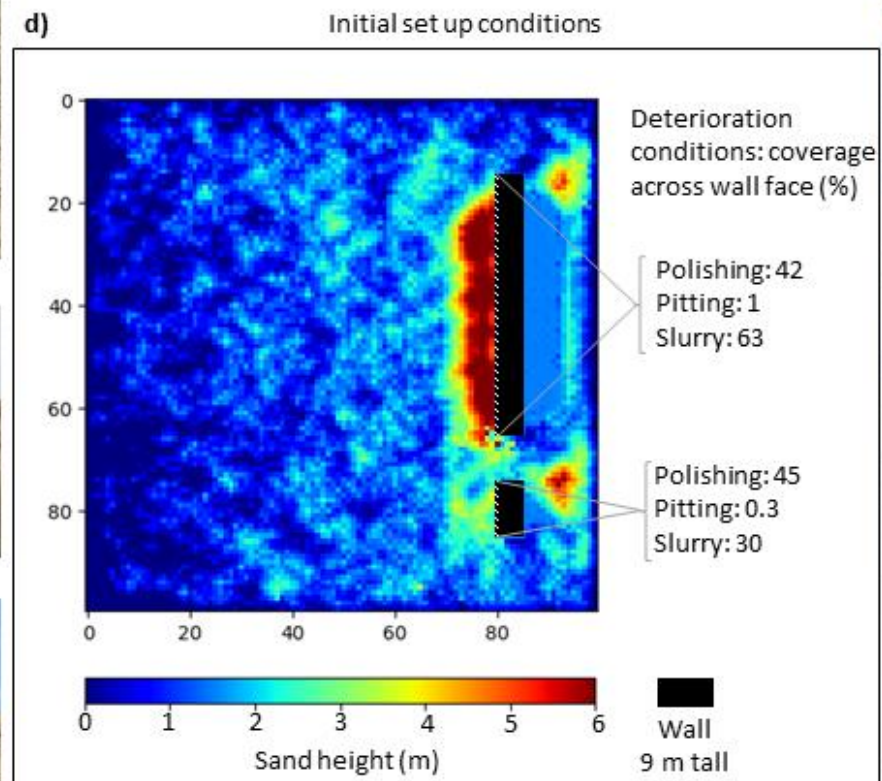
b) Dune at long wall



c) Dune at short wall



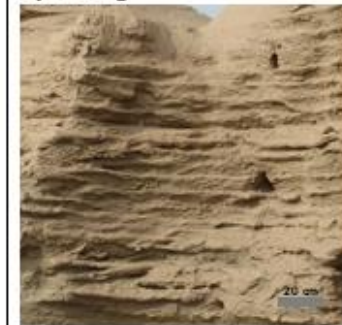
d)



e) Polishing



f) Pitting



g) Slurry



Figure 7.1: The site of Suoyang Ancient City (a-c), a plan view of the initial model setup (d) and the three major deterioration features (e)-(g).

To reflect conditions at Suoyang's inner city wall, ViSTA-HD's model space was populated with two walls: one 50 m in length and the other 10 m in length, and both 9 m high, reflecting the range of wall dimensions observed at the site. The walls were positioned perpendicular to the easterly prevailing wind (Figure 7.1d). The modelled climatic and ecological conditions were reflective of present-day conditions at Suoyang unless otherwise stated and were informed by previous studies undertaken at the site (Richards et al., 2020, 2019b). Results of deterioration risk were similar for the two modelled walls, so we only present results from the 50 m wall in the main manuscript; results for the 10 m are provided in Appendix D.

By resolving micro-scale environmental conditions occurring at the wall faces, including wind velocity and sediment movement, we used ViSTA-HD to model the risk of three dominant deterioration features at earthen heritage sites (Richards et al., 2019b, n.d.): polishing, pitting and slurry. Polishing is caused by clean wind or sediment-laden wind smoothing the surface of the material (Richards et al., 2019b) (Figure 7.1e). Pitting is caused by high-velocity or sediment-laden wind abrading the material and forming hollows (Mao et al., 2015; Richards et al., 2019b) (Figure 7.1f). Slurry is caused by rain, and wind-driven rain, weakening the cementing material between particles, which results in material being transported down the wall face under gravity and forming a drape-like surface crust (Richards et al., 2019b; Shao et al., 2013) (Figure 7.1g). The overall deterioration risk was calculated by averaging the risks of polishing, pitting and slurry. The values of modelled risk vary between 0 (representing very low risk) and 1 (very high risk). Analysable outputs from the model include wind velocity, sediment transport and rainfall across the model domain and the risks of deterioration across the wall face.

Given large uncertainties in the climate projections for northwest China (Christensen et al., 2013), we used a scenario-neutral approach to test the sensitivity of deterioration risk to possible future climates. We ran ViSTA-HD with three changes in mean annual rainfall (decrease of 10% and increases of 20% and 50%) and three in wind velocity (decrease of 1 ms⁻¹ and increases of 2 ms⁻¹ and 5 ms⁻¹), relative to the current climatic conditions (Table 7.1). Two extreme scenarios were simulated to provide a range of possible heritage responses: a ‘low change’ scenario assumed a 10% decrease in rainfall and 1 ms⁻¹ decrease in wind velocity, while a ‘high change’ scenario assumed a 50% increase in rainfall and 5 ms⁻¹ increase in wind velocity (see Table 7.1 for details). Wind velocity and rainfall parameters were deliberately pushed to extremes to understand the system response under a wide variety of conditions.

Table 7.1: Climate and conservation scenarios modelled using ViSTA-HD. A decrease in conditions is shown with a ‘-’, an increase is shown with a ‘+’.

		Current climatic conditions at Suoyang	Modelled climate Scenarios: Changes in mean annual wind velocity (ms ⁻¹) and rainfall (%)							
			Extremes		Wind			Rain		
			-1 (wind); -10 (rain)	+5 (wind); +50 (rain)	-1	+2	+5	-10	+20	+50
Conservation scenarios	No conservation strategy	Control ✓	✓	✓	✓	✓	✓	✓	✓	✓
	80% vegetation cover randomly distributed	✓	✓	✓						
	Windbreak 10m tall, 60 m upwind	✓	✓	✓						
	Windbreak 5m tall, 30 m upwind	✓								
	Two windbreaks (see above for dimensions)	✓								

We also tested the effectiveness of four nature-based conservation strategies in ViSTA-HD. Three strategies are based on different windbreak configurations (all formed of vegetation with 30% optical porosity), and the fourth involves increasing natural vegetation coverage to 80% (based on the most densely vegetated areas of Suoyang

today) (Table 7.1). The two conservation strategies that caused the greatest reduction in deterioration risk under current climatic conditions were also run in combination with the low and high extreme climatic situations to test the effectiveness of the conservation strategies under a range of future climate scenarios (see Table 7.1).

For each climatic and conservation scenario, we performed a model spinup of 400 iterations, representing 100 years in real time. This ensured our modelled system was in dynamic equilibrium representative of conditions currently observed at Suoyang. The resultant environmental and deterioration conditions at the end of the spinup period were used as initial conditions for our model runs (Figure 7.1d). The model was run for a further 400 iterations and the resultant deterioration risks were analysed and presented as our final results.

7.3 Deterioration under future climate scenarios

Figure 7.2 shows the overall deterioration risk to earthen heritage after 100 years of exposure to future environmental conditions. Current conditions experienced at Suoyang were used to generate a control deterioration risk (Figure 7.2a). This control was compared to the deterioration risk caused by potential future climatic (Figure 7.2b-i) and conservation (Figure 7.2j-m) scenarios.

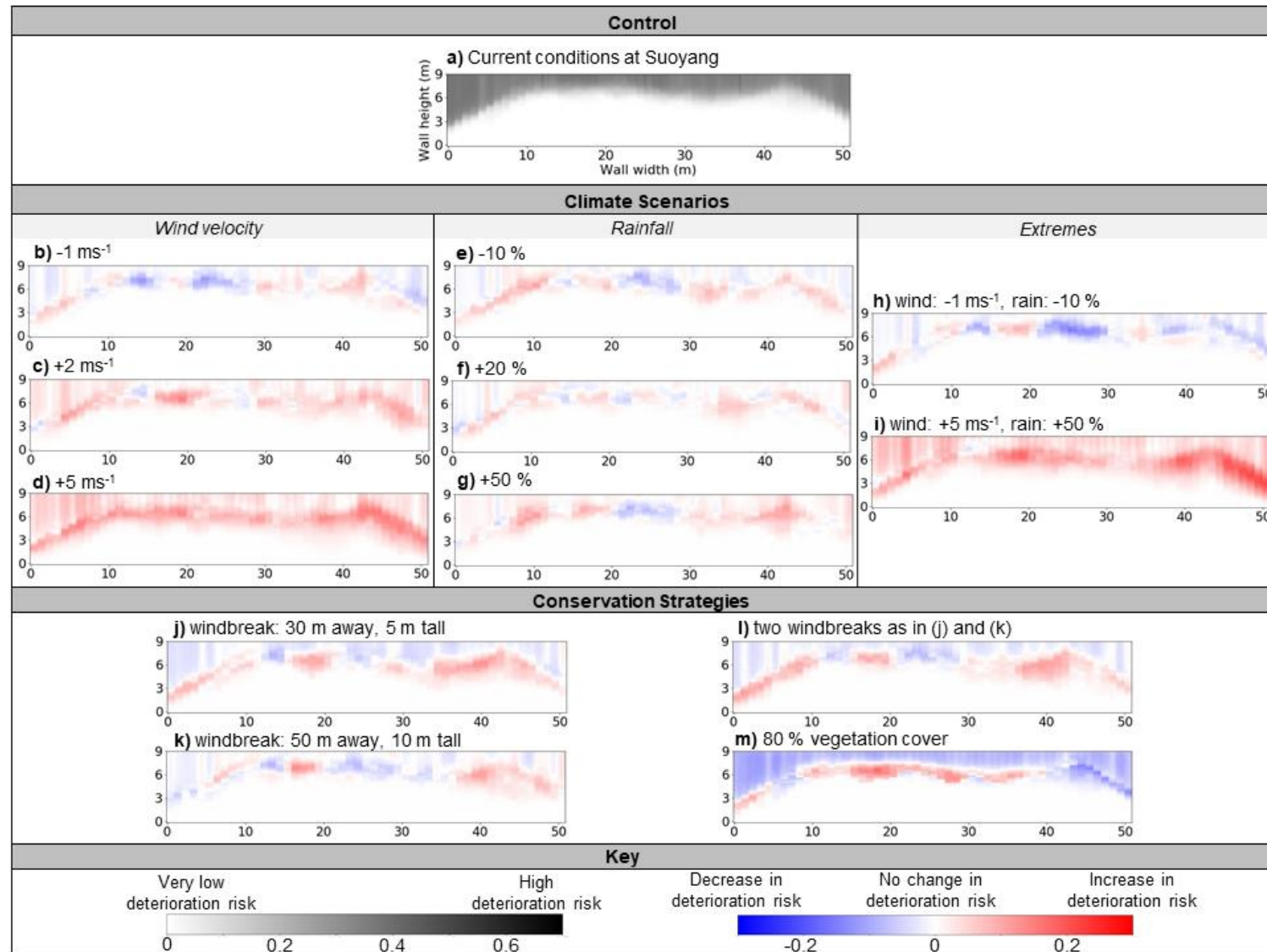


Figure 7.2: The overall risk of deterioration after 100 years under: (a) current climatic conditions; (b–i) different climatic changes; and (j–m) different conservation strategies. In panels b–m, deviations from the control results are shown with red and blue, indicating an increased and decreased risk of deterioration, respectively.

Results indicate that exposed wall faces have a medium to high risk of deterioration, while areas covered with dunes have a notably lower risk (Figure 7.2a). This implies that under present day conditions, earthen heritage sites are highly likely to continue experiencing environmentally-driven deterioration (Richards et al., 2019b), highlighting the urgent need for effective conservation strategies.

The lower risk of deterioration on areas below dune formations suggests that the development of dunes could act as a natural re-burial conservation strategy, despite sediment transport being associated with deterioration such as pitting (Agnew et al., 2004; Woolfitt, 2007). Relying on re-burial as a conservation strategy may limit access to the site. However, partial re-burial can enable the plan form of the site to be legible, while minimising the formation of features such as hollowing at the base of walls (Woolfitt, 2007). This strategy could also enhance the presentation of the ruined nature of the site (Douglas-Jones et al., 2016).

Under reduced wind velocities of 1 ms^{-1} , the overall risk of deterioration generally decreased (Figure 7.2b). Lower wind velocities resulted in lower rates of sediment entrainment (Dong et al., 2003), minimising the risk of pitting across the wall face (X. D. Wang et al., 2010) (Figure D.6). However, the lower transportation rates also resulted in slower dune build-up over the wall face (Dong et al., 2003; Tsoar, 1983). Consequently, a greater area of the wall face was exposed to environmental drivers of deterioration for a longer period of time, increasing the risk of both polishing and slurry in these areas (Figure D.6). Above this area, a reduction in driving rain caused a decrease in the risk of slurry (Blocken and Carmeliet, 2004b) (Figure D.6). As slurry tends to form surface crusts (Cui et al., 2019a), a decreased risk of slurry results in greater availability of material for

polishing, which explains why the risk of polishing increased on the upper wall face despite lower mean annual wind velocities.

Under increased wind velocities (increases of 2 and 5 ms^{-1}), the overall risk of deterioration increased substantially across the wall face (Figure 7.2c, d). The increased wind velocities, increased rates of sediment transport (Dong et al., 2003) and wind-driven rain (Blocken and Carmeliet, 2004b), resulted in higher risks of polishing, pitting and slurry across the wall face, especially with increases of 5 ms^{-1} in wind velocity (Figure D.6).

Under the modelled changes in mean annual rainfall, the overall risk of deterioration remained relatively stable (Figure 7.2e-g), although the relative dominance of deterioration features changed. Increased rainfall caused an increased risk of slurry, but formation of the crust associated with slurry reduced the risk of polishing (Cui et al., 2019a) (Figure D.7). While changes in rainfall may only have a limited impact on the overall deterioration risk, changes in the relative dominance of individual features could alter the visual aesthetics of earthen heritage sites. Therefore, if future rainfall changes, a values-based judgement would be required (Richards et al., 2018) to assess if the aesthetic impacts to the site were deemed acceptable.

Finally, combined climatic changes in mean wind velocity and annual rainfall had a notably greater impact on deterioration risk than when climatic changes occurred individually (Figure 7.2h-i). Consequently, conservation strategies need to remain effective even if multiple climatic changes occur concurrently.

7.4 Effectiveness of nature-based conservation strategies

To assess the extent to which nature-based conservation strategies minimise deterioration risk under current climate conditions, we tested four conservation strategies using ViSTA-HD: (i) a 5 m-high windbreak located 30 m away from the wall; (ii) a 10 m-high windbreak located 60 m away from the wall; (iii) two windbreaks together, as described in (i) and (ii); and (iv) 80% randomly distributed vegetation cover (up to 1.5 m tall). The deterioration risk for each conservation scenario (Figure 7.2k-m) was compared to the control risk of deterioration where no conservation strategy was implemented (Figure 7.2a).

The three windbreak configurations had a similar effect on the overall risk of deterioration (Figure 7.2k-l). Since windbreaks reduce wind velocities and trap sediment in their lee (Cornelis and Gabriels, 2005; Santiago et al., 2007), dunes built up more slowly against our simulated wall face. Consequently, the deterioration risk increased above the dune formation zone due to the slower build-up of sediment (Oliver, 2008), but decreased at the wall top due to lower wind velocities (X. D. Wang et al., 2010). Vegetation cover of 80% caused a greater reduction in the overall risk of deterioration than the windbreaks (Figure 7.2m). This suggests that under current conditions, increasing the natural vegetation cover is likely to be more effective at reducing deterioration risk at earthen sites like Suoyang than planting windbreaks. However, if a windbreak was preferable for certain reasons (e.g. wanting a strategy implemented within a contained space), shorter windbreaks would likely to be less visually intrusive on the aesthetics of the site and could be constructed using native shrubs rather than

non-native trees, which are often unsuitable for the soil conditions and climate in semi-arid areas (Cao et al., 2011).

Under present climate conditions, 80% vegetation cover is already achieved in some areas of the site (e.g. to the east of the central inner city walls). In areas of the site with lower vegetation coverage, the vegetation cover may naturally increase due to the banning of herding (e.g. goats) within the buffer zone since 2014 (UNESCO, 2014).

Landsat imagery could be used to monitor change over the coming decades (Kong et al., 2009; Zhang and Xie, 2017). Programmes to increase vegetation coverage have been widely implemented in semi-arid China (PRC-GEF Partnership, 2008), such as at Mogao Grottoes, Gansu Province, China, where rates of sediment transport were successfully minimised with no reported adverse impacts (Li et al, 2013; Tan et al 2016).

In addition, in some areas of semi-arid China, irrigation schemes have been implemented to increase vegetation cover (PRC-GEF Partnership, 2008; Dunhuang Academy, Pers. Comm. Aug 2017). Irrigation schemes can result in changes to the height of the water table; the number of insects, animals and birds in the area; and the proximity of vegetation to the earthen structure (PRC-GEF Partnership, 2008). Therefore, if irrigation schemes are implemented, additional monitoring of these factors should be undertaken at the site. If changes occurred, site managers would need to consider the relative cost/benefit of continuing the strategy.

Given that nature-based conservation strategies tend to be implemented with the intent of lasting multiple decades, these strategies need to remain effective under potential future climatic scenarios. Because of their effectiveness at minimising deterioration under current conditions, the short windbreak and 80% vegetation coverage

interventions were tested under the low and high extreme future climatic scenarios. The deterioration risk was compared to the risk of deterioration under the low/high extreme future climatic scenarios, respectively, where no conservation strategy was implemented (Figure 7.3).

When subjected to low and high extreme future climatic scenarios, 80% vegetation coverage was more effective than the windbreak at minimising polishing, pitting and the overall deterioration (Figure 7.3). The risk of slurry increased with the implementation of either conservation strategy. This increase occurred due to lower wind velocities reducing the risk of polishing and pitting, which in turn meant more earthen material was exposed to rain-driven deterioration (Richards et al., 2019b) (Figure 7.3e, f). The increased risk of slurry under the 80% vegetation coverage intervention was counterbalanced by the decreases in polishing and pitting risks, resulting in a general decrease in overall deterioration across the wall face. This was the opposite to the windbreak, which caused an overall increase in deterioration risk.

Changes in future windspeeds and rainfall could naturally alter the vegetation coverage present at the site (Bailey, 2010). Decreases in rainfall could result in vegetation elements facing additional stress from a lack of water while increases in windspeeds could increase sediment transport, resulting in increased rates of evapotranspiration and burial of individual vegetation elements (Mayaud et al., 2017a). As a result, if additional planting is required, the tolerance of chosen species to changes in moisture and wind should be considered and be gradually implemented to allow natural changes in vegetation coverage to occur.

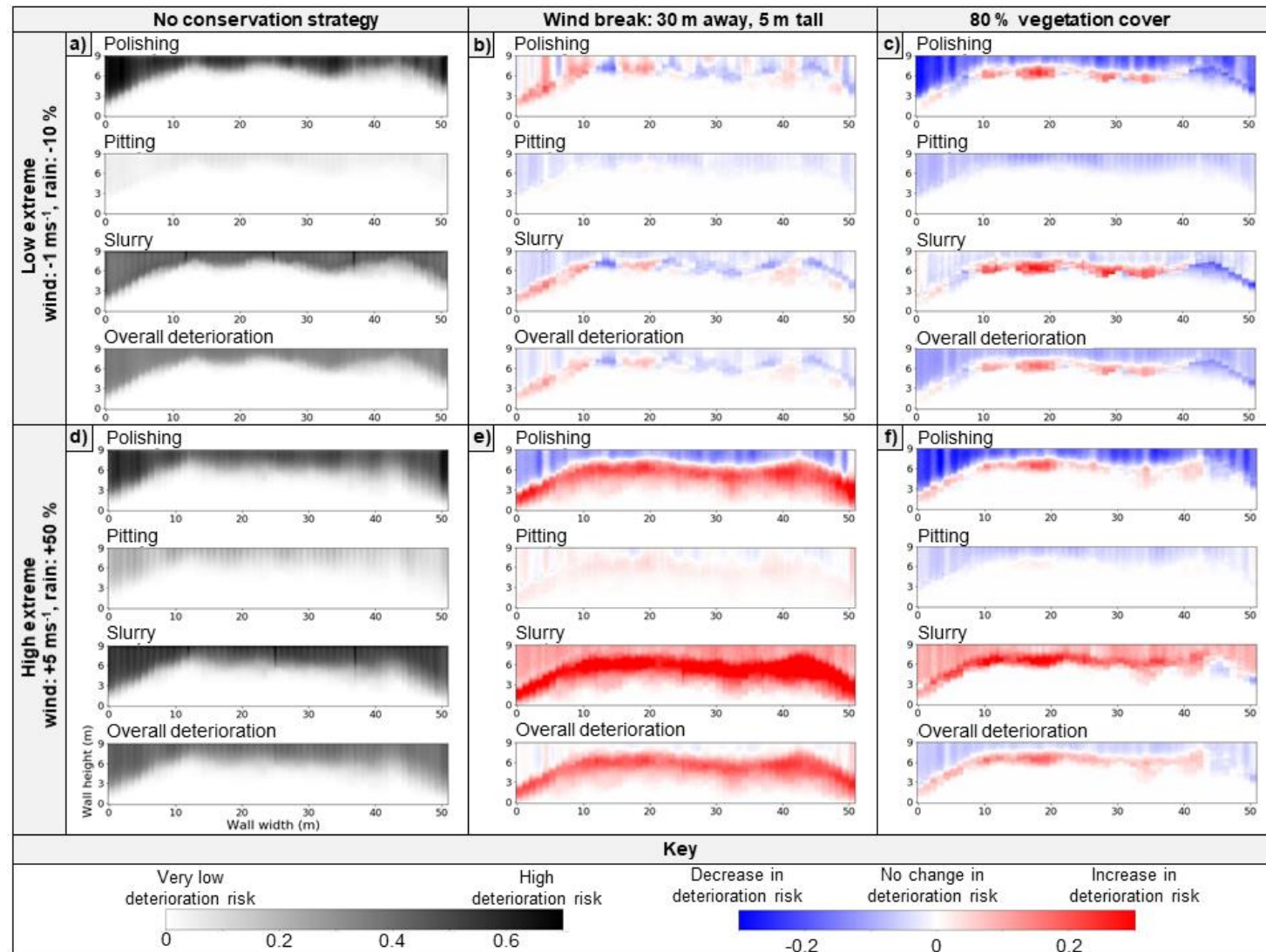


Figure 7.3: The deterioration risk and difference in deterioration risk for polishing, pitting, slurry and the overall deterioration after 100 years of model time, under (a–c) a regime of low mean annual wind velocity and rainfall, and (d–f) a regime of high wind velocity and rainfall. Different conservation strategies were applied: (a, d) no conservation strategy (control); (b, e) addition of a windbreak; and (c, f) 80 % vegetation cover.

7.5 A research-driven future for earthen heritage

ViSTA-HD provides users with the ability to iteratively assess the benefits and trade-offs of conservation decisions in the face of climatic uncertainties. As climate conditions and site deterioration change, model inputs and projects can be easily altered to provide dynamic management advice. From our application of ViSTA-HD to conditions at Suoyang, we found that increasing vegetation coverage is likely to be the most effective strategy for decreasing deterioration risk under both current and future climatic scenarios. Our results suggest this strategy is relevant to a wide variety of possible climatic scenarios. We urge conservation scientists to pursue similar strategies of combining field data with modelling to assess deterioration risk and the potential effects of their planned interventions. This approach has great potential for decreasing deterioration risk at earthen heritage sites in dryland regions around the world.

7.6 Methods: ViSTA-HD Model

The Vegetation and Sediment TrAnsport model for Heritage Deterioration (ViSTA-HD) is a coupled cellular automaton (CA) model designed to simulate the risk of environmentally driven deterioration on earthen heritage. ViSTA-HD is based on the original ViSTA model, which was designed to simulate the evolution of semi-vegetated dryland landscapes (Mayaud et al., 2017a, 2017b).

ViSTA-HD is comprised of two modules (an environmental module and a deterioration module) that interact at each timestep in the model (Figure 6.3). The environmental module simulates sediment transport dynamics around earthen walls by spatially resolving wind velocity, rainfall and sediment transport across a horizontal plane.

Environmental conditions occurring at the upwind face of the wall are stored and used as the input conditions in the deterioration module. The deterioration module spatially determines the risk of three deterioration features, polishing, pitting and slurry, commonly found on earthen heritage across the wall face as well as the overall deterioration risk.

Both the environmental and deterioration modules divide the model domain into discrete uniform grid cells. Each grid cell holds a number of properties (e.g. vegetation characteristics and height above the deposited sand, for the environmental and deterioration module, respectively). Basic rules are applied to each cell and, depending on the cell's properties, local neighbourhood operations allow dynamic responses to emerge. Empirical field data collected in semi-arid environments (Mayaud et al., 2017c, 2016b, 2016a; Richards et al., 2019b) was used to parameterise the basic rules where possible. The properties of each cell update at the end of every timestep. The state of a cell at the end of a timestep is used as the initial state of the cell at the next timestep.

7.6.1 Environmental module

The environmental module controls the wind dynamics and sediment movement.

Horizontal wind velocity is inputted at the edge of the model grid space. It interacts with vegetation and wall elements within the model, with the initial decrease in velocity and downwind distance for wind recovery being dependent of the element's height and porosity (Mayaud et al., 2017a, 2016b, 2016a). In addition, up-wind of the walls, wind velocity is reduced due to the occurrence of turbulent eddies. Airflow acceleration/deceleration is simulated over surface topography such as dune formation.

The sediment flux is a function of the wind velocity. The volume of transported sediment is determined by probabilities of erosion and deposition which are dependent on surface characteristics including the presence of vegetative and wall elements in the model space.

Further details on the environmental module is provided by Mayaud et al. (2017a).

7.6.2 Deterioration module

The deterioration module determines the risk of deterioration across the wall face for polishing, pitting, slurry and overall deterioration. The risk of deterioration is considered to be the likelihood of deterioration occurring in a given space – not the magnitude of deterioration caused. The modelled risk values vary between very low risk (0) and very high risk (1). The risk of deterioration is determined using three factors: (i) the environmental conditions impacting on the given area of the wall, (ii) the extent to which areas around the given area of the wall also experience the deterioration and (iii) previous deterioration on the given area of the wall.

More details on the deterioration module can be found in Richards et al. (2020).

7.6.3 Model runs

ViSTA-HD was used to assess the risk of deterioration: (i) under current conditions experienced at Suoyang, (ii) under potential future climate scenarios and, (iii) with the implementation of selected conservation strategies (Table 7.1). For all simulations, the model was run for 400 iterations, representing 100 years (one iterations = 3 months).

Due to the inherent variability in ViSTA-HD, each module was run until a stabilisation of the means had occurred. Consequently, for each scenario, the environmental module was run 10 times. Then for each run of the environmental module, the deterioration module was run 20 times (resulting in 200 runs of the deterioration module for each

scenario). The mean and standard deviation of deterioration risk was calculated for each cell in the model domain for each deterioration feature.

All model runs were implemented using code written in the Python® programming language by the authors. The model code is openly available from the Oxford University Research Archive (DOI: 10.5287/bodleian:nr86P0OjY).

7.6.4 Input conditions

Wind velocity and rainfall input conditions were based on meteorological data collected by an automatic weather station at Suoyang and historic records provided by the Dunhuang Academy (unpublished). At each iteration, wind velocities and rainfall volume were randomly selected from probability density functions representative of the seasonal conditions at Suoyang. Changes to the mean annual wind velocity and mean annual rainfall were implemented by decreasing/increasing the wind velocity probability density function.

Windbreaks were implemented within ViSTA-HD by placing vegetation elements with 30% porosity in a 3 m wide strip upwind of the walls. This porosity was chosen as windbreak studies have shown this to create the largest downwind zone of reduced wind velocities (Heisler and Dewalle, 1988; Santiago et al., 2007). Eighty percent vegetation coverage was implemented by increasing the proportion of randomly distributed vegetation elements in the model space. In all model runs, vegetation was assumed to remain the stable as at Suoyang image analysis has shown vegetation cover to remain stable over a decadal period (Richards et al., 2020).

7.6.5 Model implementation

We propose that findings from ViSTA-HD simulations should be implemented at earthen heritage sites using an iterative framework, which integrates field data collection with

modelling approaches. Data collection is required to ensure ViSTA-HD is initialised with site-specific climatic and environmental conditions. This ensures that the modelled deterioration risks are site-specific and relevant to decision-makers.

The suite of deterioration risks produced by ViSTA-HD can then be used to assess the relative benefits and trade-offs between conservation strategies in the context of: (i) a strategy's ability to minimise deterioration risk, as well as, (ii) other strategic factors, such as the implementation and maintenance costs, and the size and the aesthetic impact of a strategy (Richards et al., 2018). Field tests using the chosen conservation strategy should be carried out before implementation. This would ideally be undertaken over a minimum of one year to ensure the desired impact on deterioration can be achieved, without unforeseen consequences, before applying similar approaches to entire sites.

Once field tests produce the desired results, the implementation of the conservation strategy can be initiated. As this framework is iterative, ongoing monitoring of environmental processes at, and deterioration condition of, the site enables the impact of these strategies to be monitored and adjusted if required.

7.6.6 Model considerations

As with all models, ViSTA-HD cannot capture all parts of the earth system. It focuses on the risk of deterioration driven by environmental processes given the preference expressed by earthen heritage experts for conservation strategies to modify the environment rather than the historic material. Consequently, ViSTA-HD does not include other factors such as material characteristics which will also affect the absolute volume of deteriorated material. Therefore, in no circumstances should ViSTA-HD be used to

‘guarantee’ that an area will be at no risk of deterioration, instead it should be used as a research tool to aid understanding of how the environment poses risks to earthen heritage sites.

7.7 Chapter 7: Summary and implications

The Vegetation and Sediment TrAnsport model for Heritage Deterioration (ViSTA-HD) was used to assess the risk of earthen heritage deterioration under a range of future climatic and conservation scenarios. Of the scenarios tested, 5 ms⁻¹ increases in the average windspeed caused the greatest increases in deterioration risk. These risks were most effectively minimised by increasing the vegetation cover to 80%.

The ability of 80% vegetation cover to minimise deterioration risk was robust under a range of potential future climate scenarios.

To increase the relevance of these findings for practitioners and conservation managers at earthen sites, a framework for assessing the relative benefits and trade-offs (e.g. cost, management, effectiveness) for each conservation strategy could inform and improve decision-making.

Section 4

Discussion and Conclusions



8 Discussion and conclusions

The overall aim of this research has been to determine the likely impacts of the main environmental drivers of earthen heritage deterioration under current and future conditions in dryland regions. This aim has been addressed by four main objectives (Section 2.7). Given the structure of this thesis, with each of the four papers presented addressing each of the four objectives, these objectives have been discussed throughout this thesis (Figure 1.1). From these discussions, four themes have emerged that cut across the four objectives (Figure 8.1).

The first part of this discussion summarises the main findings of the papers with regard to the objectives, while the second part considers the four cross-cutting themes. These themes help address the overall aim by highlighting similarities between, as well as challenges raised by, the findings in the papers.

8.1 Thesis objectives

The objectives of this thesis were to:

- (1) assess the deteriorative impact of key individual environmental processes in the field;
- (2) evaluate the relative importance of wind and rain in driving deterioration at an earthen heritage site;
- (3) create an analytical framework that combines and evaluates the risk of multiple environmental drivers of deterioration pose to earthen heritage; and
- (4) determine the risk posed by environmental drivers of deterioration to earthen heritage under a range of future climate scenarios and conservation strategies.

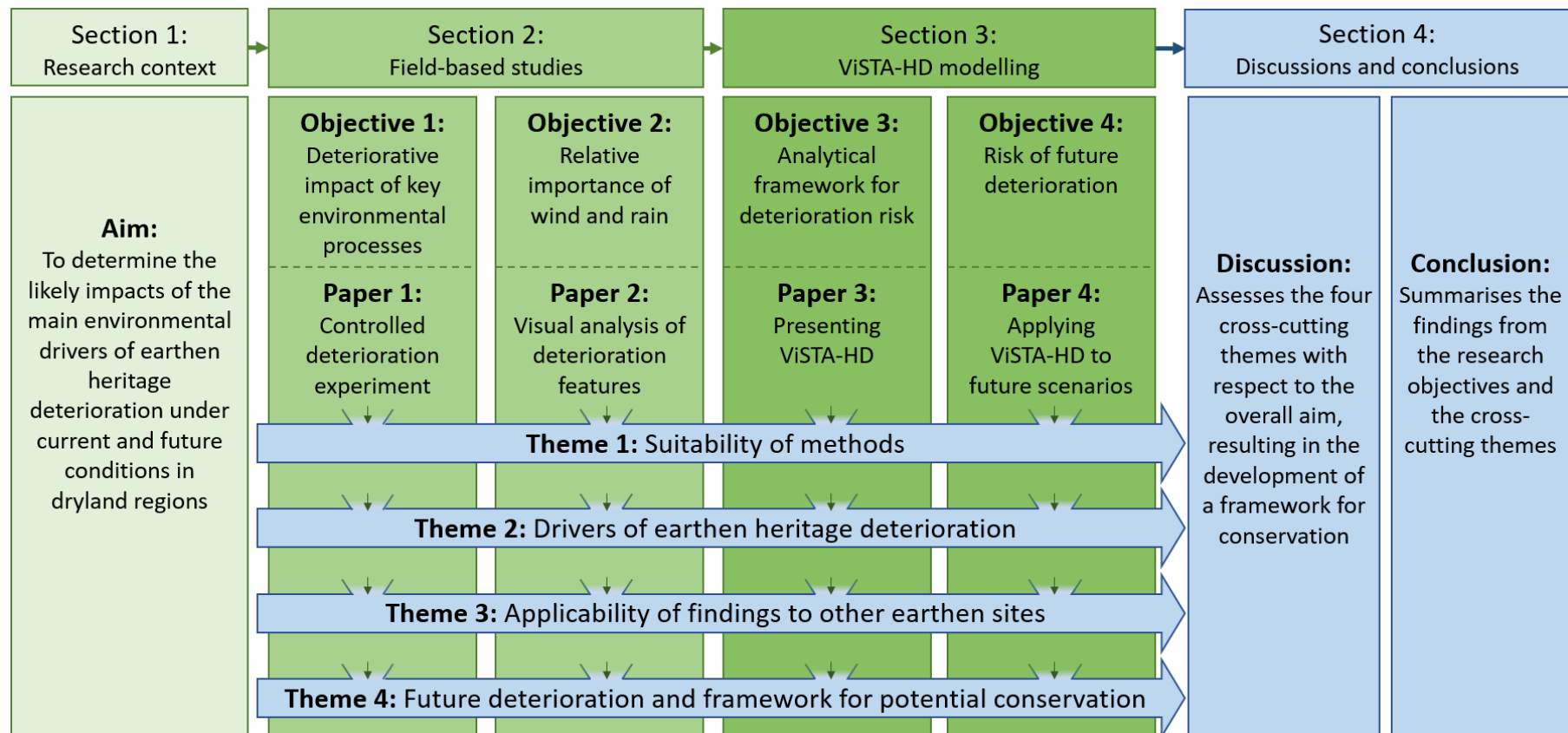


Figure 8.1: A schematic showing how the themes discussed in this section of the thesis cross-cut with the thesis objectives.

With regard to the four objectives, findings in this thesis showed:

Objective 1. Both wind and rain caused deterioration to earthen heritage. Wind removed loose particles from the wall surface causing polishing and pitting, while rain weakened the cementing material transporting material down the wall face causing gully formations (Figure 4.4). The morphological differences in wind-driven and rain-driven deterioration features, suggested they could be used to infer past environmental drivers of deterioration.

Objective 2. Wind is an important driver of earthen heritage deterioration in dryland environments. Individual wind events have a low magnitude impact but frequently occur above the threshold for causing deterioration. This causes wind to be an important initiator of deterioration. In addition, the cumulative impact of wind is such that the most severe deterioration occurs on areas exposed to the prevailing wind (Table 5.2).

Objective 3. Cellular automata modelling provides a reliable framework to simulate the interactions between environmental processes and the risk these processes cause to earthen deterioration. The cellular automata model developed in this thesis, VISTA-HD, accurately captured patterns of deterioration seen at Suoyang Ancient City and could be applied to other sites without the need for extensive additional calibration (Figure 6.10).

Objective 4. Future changes in windspeed are likely to have significant impacts on the risk of earthen heritage deterioration. Increasing natural vegetation cover was found to be the most effective conservation strategy at minimising the risk of deterioration under a range of possible future climatic scenarios (Figure 7.2 and 7.3).

8.2 Cross-cutting themes

In addition to the findings specifically addressing each of the thesis objectives, I have identified four themes that have emerged that run through this thesis (Figure 8.1). These themes aid discussion between the four objectives, helping to highlight common findings as well as challenges in addressing the overall aim of this thesis.

The four themes are:

- (i) the suitability of methods used to undertake earthen heritage research;
- (ii) the drivers of earthen heritage deterioration;
- (iii) the applicability of findings to other earthen heritage sites; and
- (iv) future impacts of environmental drivers of earthen heritage deterioration and potential ways forward for conservation.

8.3 Theme 1: Suitability of methods used in earthen heritage research

The first cross-cutting theme, which helps address the overall aim of the thesis, focuses on the methods used to assess the impact of environmentally-driven earthen heritage deterioration. The extent to which findings from each of the four papers addressed the overall aim of this thesis was underpinned by the effectiveness of the method(s) chosen.

The methods used in this thesis need to assess: (i) the impact of the main drivers of deterioration, both individually and together and, (ii) the impact of past, present and future environmental conditions on deterioration, while, also (iii) being feasible to implement, both practically and ethically, at a range of earthen heritage sites. Given that

in this thesis I have combined a range of methods not commonly used together (Figure 3.8), the effectiveness as well as the limitations of the methods used are discussed.

8.3.1 Methods assessing individual and multiple drivers of deterioration

Methods that investigate the impact of individual environmental conditions on earthen heritage can help develop our understanding of the main drivers of deterioration (Table 2.4). As seen in the controlled field experiment (Chapter 4, Paper 1), separately applying wind and rain processes to earthen materials meant we could assess the erosive impacts of wind and rain at various magnitudes (Figure 4.4). This helped to determine thresholds for deterioration, as well as the relative deteriorative impact of individual environmental factors. While these experiments simplify earthen heritage deterioration to one, singular driver, results from these experiments were important in informing the interpretation of the geomorphological signatures (Chapter 5, Paper 2; Section 5.2.2) and defining quantitative thresholds for deterioration risk within ViSTA-HD (Chapter 6, Paper 3; Figure 6.5).

Furthermore, images taken by the Dunhuang Academy of the large test walls 1.5 years after the fieldwork undertaken in this thesis (meaning the walls were exposed to the environment for approximately 2.5 years) show the presence of deterioration features similar to those created during the controlled field experiment (Figure 8.2). This suggests that despite controlled field experiments being critiqued for simulating processes of higher magnitude and intensity than those naturally occurring (Beckett et al., 2020), the induced deterioration mechanisms can still be representative of those occurring naturally even after a relatively short period of time (months to years).

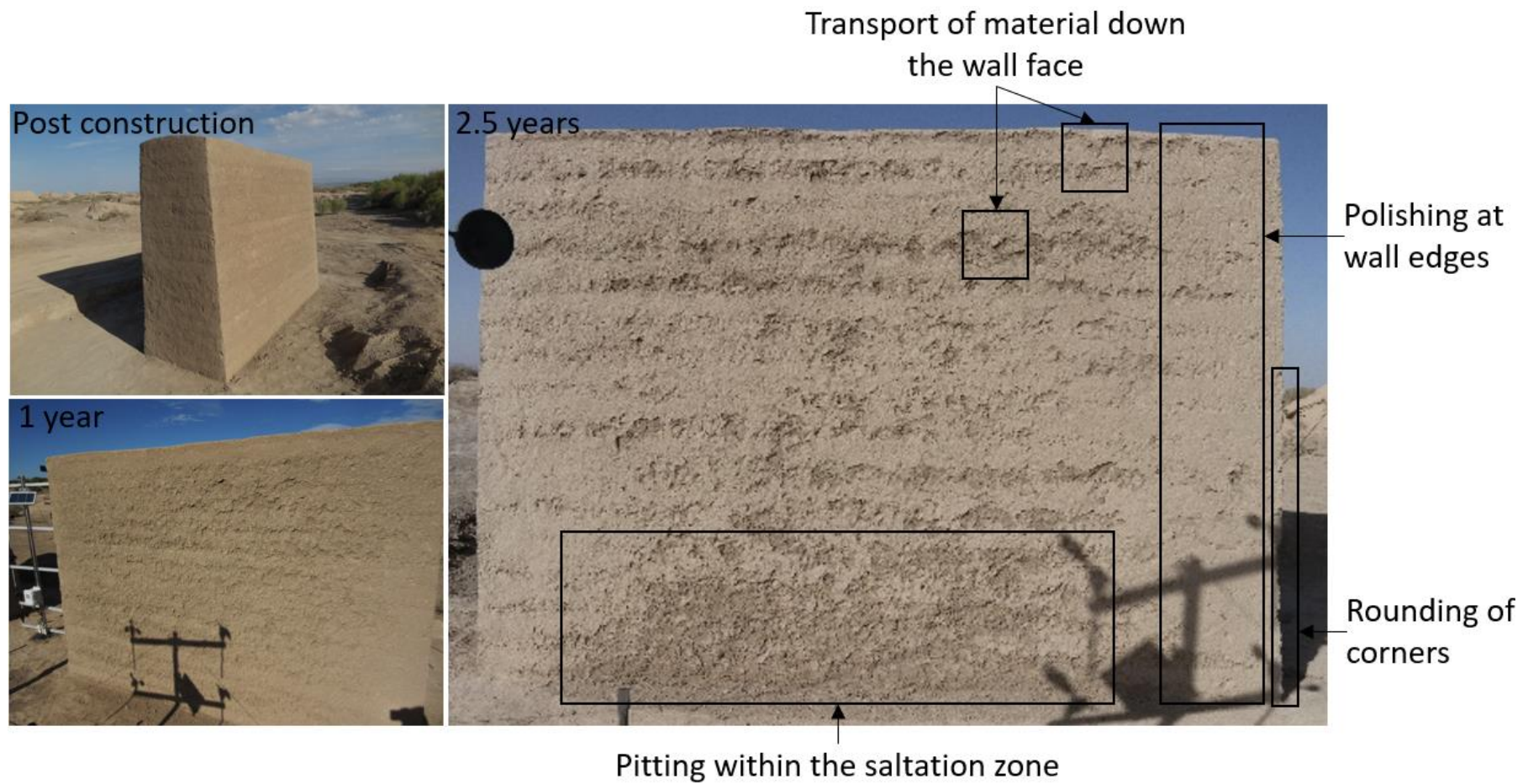


Figure 8.2: Test Wall 1 post construction and after being exposed to the environment for 1 year and 2.5 years. Features present on the wall after 2.5 years that are similar to those produced in the controlled field experiment in Chapter 4 (Paper 1) are highlighted. Photo credit: Dunhuang Academy.

The design of controlled deterioration experiments is heavily reliant on the researcher's selection of environmental processes (Table 2.4). This selection is likely to be influenced by previous findings, the availability of meteorological data, as well as the availability of technology to simulate environmental processes. This means that less well-known conditions or those that are difficult to simulate, such as, lightning strikes, are not commonly investigated.

To address such challenges, many scientific fields have a long history of taking a systems approach to identify key drivers within a given system. By considering attributes of a whole system, a systems approach enables complex and emergent behaviours to be explored (Jackson et al., 2010). For example, Alexander von Humboldt pioneered systems thinking by viewing everything in nature as interconnected and used his concept of *Naturgemälde* to present the sense of unity within nature (Nature Editorial team, 2019). Other fields have since also taken similar approach with, for example, clinical research using 'systems medicine', to provide a holistic approach to understanding disease pathways or treatment procedures (Thompson et al., 2015). This is also seen in built heritage research: Richards et al. (2019a) recently argued that reconceptualising built heritage within an Earth System Science framework would enable a more sustainable approach for understanding and conserving heritage.

For earthen heritage research, using methods that enable a wider systems approach could help consider a range of potential deterioration processes within the experimental design. This would minimise the risk of experiments being predetermined to reinforce the current discourse. Applying methods, such as geomorphological signatures (Chapter 5; Paper 2) and cellular automaton modelling (Chapters 6 and 7; Papers 3 and 4), meant

interactions and feedbacks between multiple environmental drivers of earthen heritage were able to be considered within a systems approach. Had I used methods in this thesis that only looked at one driver, the importance of other drivers, as well as the interactions between drivers would have been missed.

In the future, as technology develops, alternative methods will also become possible. For example, the Dunhuang Academy recently opened their Multi-field Coupling Laboratory. This facility has been designed to undertake environmental testing within large room-sized chambers able to control insolation, temperature and precipitation (including snowfall) (Figure 8.3; Wang et al., 2015). This provides the potential for experiments to test the deteriorative impact of combinations of environmental drivers on test walls that were multiple meters in length and height, combining the benefits of the controlled nature of the field experiment in Chapter 4 (Paper 1) with the complexity of process interactions studied in the subsequent chapters.

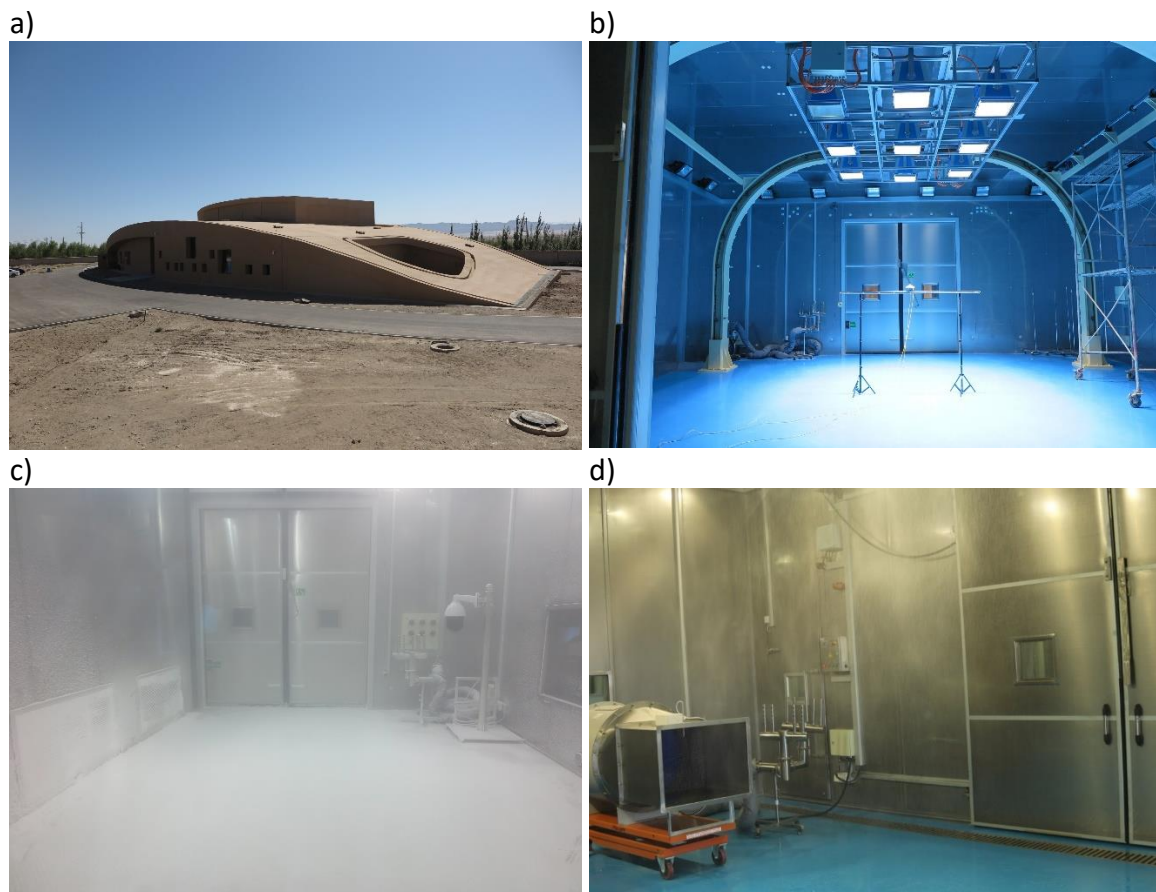


Figure 8.3: The Multi-field Coupling Laboratory at Dunhuang Academy. a) The lab building, b) the Summer test Chamber, c) the Winter test chamber and d) the wind and rain chamber. Photo Credit: Dunhuang Academy.

8.3.2 Methods assessing past, present and future deterioration

The methods we used to investigate the current impacts of drivers of deterioration at Suoyang had to address both the frequency and magnitude of the environmental drivers, as well as capturing the variation in deterioration across individual wall faces (Chapters 4 and 5; Papers 1 and 2). The methods employed were able to make use of both test and historic walls, as well as field and modelling techniques (Figure 3.8).

To assess the risk of future deterioration, I took a modelling approach (Figure 3.1). A conceptual schematic was used to suggest how future rates of deterioration would change as the frequency or magnitude of windspeeds and rainfall increased (Chapter 4, Paper 1; Figure 4.6). However, whilst these conceptual diagrams can be highly useful for

developing testable hypotheses, Figure 4.6 was not spatially explicit and, as a result, is highly likely to have missed a significant amount of complexity associated with earthen heritage deterioration.

To address this, the CA model, ViSTA-HD, was developed to capture complex interactions between dryland environmental systems and earthen heritage in a spatially explicit manner (Chapter 6, Paper 3; Figure 6.3 and 6.5). By running ViSTA-HD using a range of scenarios to capture uncertainties in future climate projections, it is possible to understand how the risk of deterioration could change in the future (Chapter 7, Paper 4; Figure 7.2). As we continue to increase our understanding of earthen deterioration processes, we should continue to review and update models, such as ViSTA-HD, with the aim to model the *volume* of material loss from earthen heritage structures, rather than *risk* of deterioration. By explicitly modelling the volume of material loss, the development of larger deterioration features such as slumps and turrets (seen in Figure 5.6) could be captured.

In addition, developments in computer technology will likely result in other modelling approaches, such as computational fluid dynamic models, becoming less computationally expensive. These developments could result in other finer-scaled modelling methods becoming computationally feasible, enabling deterioration to be investigated at higher resolutions (e.g. Figure C.15). As such, future work should continue to compare the efficacy of a range of modelling approaches, balancing the computational requirements for the end-user (e.g. researcher/practitioner) to implement the model, with the resolution of the data produced by the model.

I have not explicitly investigated past drivers of deterioration in this thesis. Future research on this topic would provide critical insights into how environmental processes have caused earthen heritage deterioration over multiple centuries. However, to address the impact of past deterioration feature on current processes, the legacy of historical deterioration features on subsequent deterioration processes was assessed in the field (Chapter 5, Paper 2; Table 5.3) and within ViSTA-HD (Chapter 6, Paper 3; Figure 6.5). ViSTA-HD could be applied as a hind-casting tool by using environmental processes representative of historic conditions as input conditions. These results could help inform our understanding of how future environmental conditions could drive deterioration over multiple centuries. For sites that do not have archives of environmental records, proxies such as tree rings (Tian et al., 2007), speleothems (Wolff et al., 2017) and sediment accumulation (dunes) (Buckland et al., 2018) could be used to infer such records.

8.3.3 Application at earthen heritage sites

My research highlights the ethical and practical considerations when selecting methods for use in earthen heritage research. I was not able to use methods that caused deterioration to the historic walls (see Section 2.6.2), because the value of earthen heritage sites is dependent on the presence of authentic material remaining *in situ* (ICOMOS China, 2015; Richards et al., 2018). Despite these limitations, methods I have used, such as the visual analysis of geomorphological features (Chapter 5, Paper 2) and the development and application of VISTA-HD (Chapters 6 and 7, Papers 3 and 4), have shown that non-destructive approaches can successfully be applied to earthen heritage sites to investigate complex deterioration patterns.

The methods used in this thesis also demonstrate the research value of test walls. The regular structure of the large test walls meant that environmental processes such as wind flow could be measured around the walls without having to account for irregular wall shapes (e.g. Figure 6.2). Furthermore, by not being perceived as having heritage value, the walls could be exposed to semi-destructive methods increasing the potential number of methods that could be utilised.

However, it should be noted that the test walls are surrogate objects used for research (Strlič, 2015). By using a contemporary structure to study the drivers of earthen heritage deterioration, the lack of material maturity is likely to have influenced results to some extent. At Suoyang, this influence was reduced by using traditional building techniques and materials (Dunhuang Academy, unpublished; Figure 2.4). However, without being able to conduct comparative tests on the historic material, quantifying the extent of this influence is highly challenging and further research is needed. Also, the construction of test walls is expensive and time-consuming (walls have a minimum six-month curing time). This means anyone using test walls has to be mindful of minimising damage to ensure that future researchers can also benefit from the presence of these walls. For my research, this meant that the number of tests runs deployed in the controlled deterioration experiment was limited to three runs each of clean wind, sediment laden wind and wind driven rain over small spatial areas (Chapter 4, Paper 1; Table 4.1).

This thesis also highlights the range of low- and high-tech methods that can be usefully applied to earthen heritage research according to the level of detail required (Figure 3.8). For example, the semi-quantitative visual assessment used only a pencil and paper (Section 5.2.2, Chapter 5, Paper 2) but, nonetheless, provided valuable information

about the visible deterioration features on the test and historic walls. In comparison, the Creaform Handy SCAN 700 3D™ laser scanner captured deterioration features invisible to the naked eye, enhancing our ability to understand environmental drivers of deterioration (Chapter 4, Paper 1; Figure 4.4). The remote nature of many earthen heritage sites means that there can be limited capacity to repair technical equipment. As such, for earthen heritage research, it is pragmatic to use the level of technology that will provide a sufficient quality of data to answer the objective/ question without “over-teching” the methods.

Combining non-field-based methods, such as the modelling or laboratory experiments, with fieldwork can minimise the duration of the fieldwork, which is often expensive. Results from combined approaches can also inform and refine research undertaken on subsequent fieldwork trips. Also, as the COVID-19 pandemic has highlighted, not being solely reliant on field data but instead being able to undertake desk-based research, is useful to enable the continuation of research when unexpected extreme circumstances prevent field- and lab-based work.

8.3.4 Multi-method approach

This thesis demonstrates the need for a range of methods to determine environmental drivers of deterioration. As earthen heritage research is predominantly disseminated through academic papers, findings are commonly limited to results derived from one or two methods due to word limits enforced by journals (Table 2.4). By combining methodologies from four papers, in this thesis I show how a multi method approach can successfully address the complexity of environmentally-driven earthen heritage

deterioration, as well as the practical challenges caused by working at an earthen heritage site.

Results further highlight the need for social and natural science research to be undertaken in parallel to ensure the physical processes are studied within the context of the site's heritage value. The success of the range of contrasting methods suggest that earthen heritage researchers should maintain an outward looking approach and, where needed, adapt methods used in other disciplines. The flexibility in the approach used in this thesis could be used by other researchers investigating earthen heritage deterioration and highlight avenues for future research.

8.4 Theme 2: Drivers of earthen heritage deterioration

The second theme running throughout this thesis is the deteriorative impact of environmental conditions on earthen heritage. By considering the four papers together, the combined results highlight:

- (i) the importance of wind as a driver of present and future earthen deterioration; and
- (ii) the role of other factors driving deterioration, including rain, as well as other environmental, human and natural hazard drivers.

8.4.1 The importance of wind as a driver of earthen heritage deterioration

The importance of wind as a driver of earthen heritage deterioration has emerged throughout this thesis. In the controlled field experiment, the deterioration caused by wind was predominantly invisible to the naked eye, while rain-driven deterioration caused notable movement of material down the wall face (Chapter 4, Paper 1; Figure

4.4). However, this experiment also highlighted the ability for windspeeds as low as 12 ms^{-1} to deflate loose particles from earthen material (Figure 4.4). As Suoyang was exposed to more than 55,000 wind events greater than 12 ms^{-1} between 2015 and 2016 (Dunhuang Academy, unpublished), this suggests that the high frequency occurrence of wind events could cause a significant cumulative impact.

Wind was found to be an important initiator of deterioration at Suoyang, as well as having significant cumulative deteriorative impacts (Chapter 5, Paper 2). The most severe deterioration, in the form of turreting, occurred on the areas exposed to the prevailing wind and in zones of wind acceleration (Figure 5.6).

Results from the ViSTA-HD model (Chapters 6 and 7, Papers 3 and 4) demonstrated the continued importance of wind as a future driver of earthen deterioration. In order to minimise further deterioration risks, this suggests that conservation strategies should seek to reduce windspeeds at earthen heritage. This is further discussed in Section 8.6.1.

8.4.2 Other drivers of earthen heritage deterioration

Rain was found to cause significant amounts of material loss with the rapid formation of incipient gullies (Chapter 4, Paper 1; Figure 4.4) and extensive areas of slurry present on the wall faces exposed to the prevailing storm direction (Chapter 5, Paper 2; Table 5.2).

This ability for rain to drive the movement of large volumes of earthen material has been widely noted (e.g. Bruno et al., 1968; Bui et al., 2009; Fodde and Khan, 2013).

However, my research at Suoyang (Chapters 5 and 7, Papers 2 and 4) indicate that the cumulative impact of rain as a driver of earthen heritage deterioration is limited by the low frequency nature of rainfall events in dryland environments (Figure 5.7 and 7.2),

illustrated by there being only with 15 rain events at Suoyang in 2018 (Dunhuang Academy, unpublished).

Understanding the frequency and magnitude of drivers of deterioration emphasises the importance of considering drivers of deterioration within their climatic context.

Frequent drizzle events commonly occurring in humid environments are likely to cause the earthen material to remain saturated for longer, compared to infrequent rain storms followed by high evaporation rates in a dryland environments (Bui et al., 2011; Q.-B. Bui et al., 2014). Therefore, even if the same volume of rainfall occurred in the two environments, the resultant deterioration is likely to differ. For example, short, intense rainfall events promote surface runoff, while longer lighter rainfall events could promote internal saturation, mobilising salt within the earthen structure (Shen et al., 2017). This emphasises the need for further experiments that mimic the variable nature of rainfall in dryland environments, like the controlled field experiment (Chapter 4; Paper 1), to further investigate how such climatic differences impact deterioration.

In addition to wind and rain, other environmental conditions (Table 2.2), human factors and natural hazards can also pose a risk to earthen heritage deterioration. Table 8.1 presents the risks posed by these factors.

Environmental conditions including variations in temperature (Mao et al., 2008; Shao et al., 2013), precipitation other than rain, such as snow (Pu et al., 2016a), and vegetation growth (F. Wu personal communication, September 2017), have all been found to be factors driving deterioration at sites in northwest China (Table 2.2). The extent to which these conditions drive deterioration at Suoyang needs further research and could be

undertaken using facilities such as the Multi-field Coupling Laboratory at the Dunhuang Academy (Figure 8.3).

Table 8.1: Environmental, human and other drivers contributing to earthen heritage deterioration

Driver	Deterioration process
<i>Environmental</i>	
Temperature	The expansion and contraction of particles within the soil matrix, can weaken particles from the cementing material (Rainer, 2008; Sun et al., 2011).
Precipitation	The addition of moisture into the earthen material can enable other weathering processes such as freeze-thaw and salt weathering (Cui et al., 2017; Shen et al., 2017; Zhao et al., 2012).
Vegetation	Root growth can weaken soil structures and branches can scrape away at the surface of earthen material (Gyssels et al., 2005; Mohammad and Adam, 2010).
<i>Human</i>	
Tourism	Footfall may weaken historic material. This is especially likely if purpose-built paths are not built or tourist stray off the paths. In addition, tourists can deliberately take material away from a site or cause vandalism (Rodway-Dyer and Ellis, 2018).
Farming	Grazing animals may weaken the earthen material (Evans, 1998).
<i>Other</i>	
Natural Hazards (e.g. earthquake)	Natural hazard such as earthquakes can cause sudden high magnitude shocks to a site. Seismic waves can cause structural failure of earthen structures (Newmann, 2010).

In addition, humans can cause significant damage at heritage sites by altering landscape processes through actions such as farming and tourism (Table 8.1; e.g. Cigna and Tapete, 2018; Lazzari et al., 2006; Ravankhah et al., 2017). At Suoyang, the impact of farming is highly controlled with, for example, all farming being prohibited in the buffer zone around Suoyang (UNESCO, 2014). This complete ban on grazing in the buffer zone may limit deterioration caused by animal trampling and the absence of grazing animals on the land could cause increases in vegetation cover. This could further reduce deterioration at the site by lowering windspeeds and trapping sediment (Chapter 7, Paper 4; Figure 7.2). However, if vegetation grows on or near the historic walls,

processes such as root growth and branch scraping could increase deterioration (Historic England, 2015).

Tourism at Suoyang is moderately low with the site receiving around 12,600 visitors in 2017 (Dunhuang Academy, unpublished). However, this number is likely to increase with the development of a tarmacked road to the site and the increased publicity that comes with gaining world heritage status. As a result, tourist infrastructure needs to be developed to minimise the deterioration at the site with, for example, the implementation of prescribed walkways and capping the daily/yearly number of visitors to the site (UNESCO, 2017). This could be funded by the additional revenue generated by tourism to the site.

Finally, natural hazards can also drive earthen heritage deterioration (Table 8.1). The location of earthen sites in central Asia mean that many sites, including Suoyang, are in zones vulnerable to earthquakes (UNESCO, 2014). These high magnitude seismic events can cause extensive damage to earthen heritage and, as a result, pose a substantial threat to earthen sites. To mitigate against such threats there has been a large body of research investigating how to effectively protect earthen structures against seismic shocks (e.g. Bui et al., 2020; Newmann, 2010; Zhou and Liu, 2019). Any site within an earthquake zone should adopt appropriate strategies to minimise the risk of seismic damage. This should be done in conjunction with, and not instead of, strategies that minimise environmental risks (Figure 2.2). These sites need to be protected from both the high frequency (environmental) and the high magnitude (natural hazard) drivers of deterioration.

8.5 Theme 3: Applicability of findings to other earthen sites

The third theme running through this thesis addresses the ability to apply findings from Suoyang to other earthen heritage sites. Given the abundance of earthen heritage sites in northwest China and central Asia (Figure 2.1), with many experiencing severe deterioration, this discussion focuses on the applicability of findings in this thesis to sites in this geographic region. To assess the applicability, three factors are considered:

- (i) material properties;
- (ii) history; and
- (iii) climatic conditions.

8.5.1 *Material properties*

Extensive research has shown that the material properties of earthen material can impact its susceptibility to erosion (Table 2.4; Bui and Morel, 2009; T.-T. Bui et al., 2014; Du et al., 2017; Wu et al., 2012). Whilst there is some variation in material properties at sites in northwest China, the range of properties found at Suoyang is broadly representative of material properties found at other sites (Figure 8.4).

Furthermore, sites with material properties outside the range of those found at Suoyang, such as Jiaohe Ancient City (Shao et al., 2013) and the Ming section of the Great Wall of China (Pu et al., 2016a), have still been shown to suffer from similar deterioration patterns to those at Suoyang (Figure 8.4). As such, this suggests commonalities in the deterioration processes even with variations in the material properties.

a)

Site	Province						Grain Size (mm)				Deterioration features				Studies
		Dry density (g cm ⁻³)	Porosity (%)	Water Content (%)	Compressive strength (MPa)	Tensile strength (MPa)	<0.075	0.075-0.1	0.1-0.25	0.25-0.5	Polishing	Pitting	Slurry	Slumps/ collapse	
Suoyang (historic site)	Gansu	1.54-1.76	32.7-39.0	0.6-1.76	0.26-1.3	0.03-0.7	30.81-42.16	7.56-24.86	17.29-33.5	6.48-17.29	✓	✓	✓	✓	Dunhuang Academy, Unpublished
Suoyang (large test walls)	Gansu	1.65- 1.75	-	-	-	-	14-22	45-61	25-32	0-1	✓	✓	✓	x	Dunhuang Academy, Unpublished
Ming Great Wall	Gansu	1.51-1.92	29.1-68.0	1.06-9.30	-	-	-	-	-	-	✓	✓	✓	✓	Pu et al. (2016a); Du et al. (2017)
Hecang Fortress	Gansu	1.64-1.91	29.08-39.6	-	-	-	38.5-95.1	-	-	-	✓	✓	✓	✓	X. Wang et al. (2010)
Yumen Pass	Gansu	1.87	32.4	1.1-2.9	-	-	83-91.5	-	-	-	✓	✓	✓	✓	X. Wang et al. (2010)
Milan Ancient City	Xinjiang	1.53	42.22	0.68	-	-	24.25	47.4	14.8	7.25	✓	✓	✓	✓	X. D. Wang et al. (2010)
Jiaohe Ancient City	Xinjiang	1.42-1.72	40.74-42.65	1.76-2.41	1.05-4.25	0.34-0.76	18	57	25	0	✓	✓	✓	✓	Z. Li et al. (2011); Shao et al. (2013)
Gaochang Ruins	Xinjiang	1.853	30.7	2.71	-	-	-	-	-	-	✓	✓	✓	✓	Zhao et al. (2016)

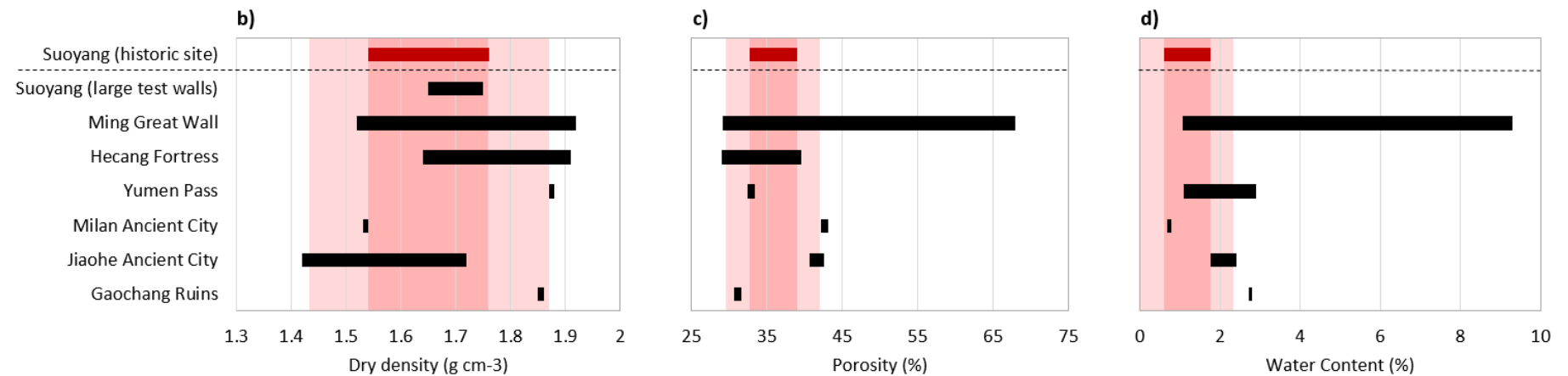


Figure 8.4: (a) Properties of historic material at Suoyang and a selection of earthen heritage sites in northwest China with (b-d) illustrating the dry density, porosity and water content, respectively. The dark pink areas show the range in material properties recorded at Suoyang with the light pink areas showing +/- 50% of Suoyang's range.

However, findings within this thesis should not be applied to sites constructed from other earthen materials (e.g. those mentioned in Table 2.1) as the difference in material characteristics is likely to significantly alter the susceptibility to environmental drivers of deterioration (Rainer, 2008).

8.5.2 History

The historic context of each site is also important when considering the applicability of findings from Suoyang. The use of rammed earth in China as a construction technique dates back to the nomadic peoples living in the area over 4000 years ago (Jaquin et al., 2008). The technique was refined with the implementation of the frame method (Figure 2.4) during the Han Dynasty (206 BCE – 221 CE) and then extensively used from the Six Dynasties Period (221 CE-581 CE) (Jaquin et al., 2008). This suggests that Suoyang is likely to have been built using similar techniques to many other trading settlements, such as Milan City and Bashbaliq City, constructed at a similar time (Figure 8.5a). It also suggests that even for settlements and defensive structures that pre-date Suoyang's construction, similar techniques are also likely to have been used (Figure 8.5a).

Many settlements on the ancient Silk Road gradually fell into disuse around the 13th to 15th century due to the decline in overland trade (Xie et al., 2007a). Therefore, like Suoyang, many earthen heritage sites in this region have been without upkeep, and exposed to environmental drivers of deterioration, for many hundreds of years (Figure 8.5a). As such, this suggests that the cumulative impacts of environmental drivers of deterioration are likely to have similarly evolved over similar durations at other earthen sites in northwest China and central Asia (UNESCO, 2014).

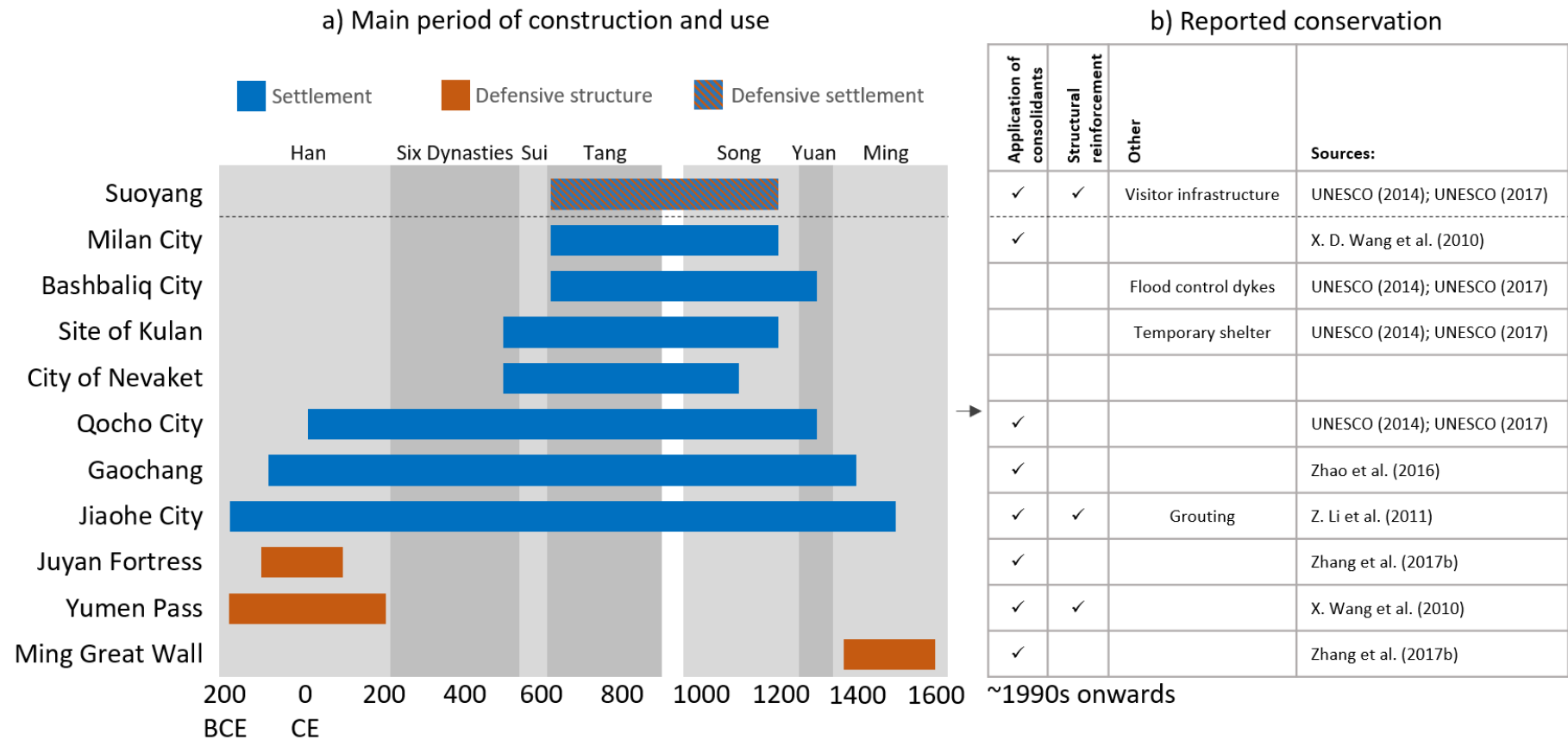


Figure 8.5: A comparison of historic context of Suoyang to other earthen heritage sites in northwest China and central Asia with regard to a) the main period of construction and use and b) contemporary reported conservation strategies.

The contemporary conservation history of a site should also be considered, as conservation treatments could have impacted the current material properties (Table 2.3). Contemporary treatments, such as the application of consolidants and the addition of structural reinforcements, have commonly been used at many earthen sites to decreasing the erodibility of the earthen material (Figure 8.5b). While such treatments typically change the material properties of a site (Table 2.3), the large variability already present in untreated samples suggests that even once the treatment has been applied, the material properties are likely to remain in the range where findings from Suoyang could be applied (Figure 8.4). However, further research for such sites (or for specific areas of sites that have undergone treatment) would be beneficial to ensure that interactions between the conservation treatment and the environmental drivers of deterioration did not cause any surprising or unforeseen negative impacts.

8.5.3 Climatic conditions

The applicability of results in this thesis to other earthen heritage sites is also dependent on a site's climatic conditions. For earthen heritage sites located in similar semi-arid environments to Suoyang (Figure 3.6), such as Yumen Pass (X. Wang et al., 2010), levels of risk posed by environmental drivers of deterioration are likely to be similar.

Therefore, findings from Suoyang could be assumed to be relevant to these sites.

However, earthen heritage sites are located across a spectrum of dryland environments (Figure 2.1). Within the Silk Roads World Heritage listing, which spans over 5,000 km, a range of climates are found from dry sub-humid central China through to arid northwest China, Kyrgyzstan and Kazakhstan. Results from ViSTA-HD (Chapter 7, Paper 4; Figure 7.2) suggest that in areas with lower rainfall (i.e. more arid environments than Suoyang),

the importance of rain as a driver of deterioration is likely to decrease, concomitantly increasing the relative importance of wind as a driver of deterioration (Figure 8.6). In contrast, in areas with higher rainfall (i.e. less arid environments than Suoyang), the increasing frequency and volume of rainfall events is likely to increase the risk of rain-driven deterioration (Figure 8.6).

This suggests that the overarching findings from Suoyang can be applied to sites located in a range of dryland regions but the balance between wind and rain as the main drivers of earthen heritage deterioration is likely to alter depending on the aridity of the site. However, given the effectiveness of increasing natural vegetation cover at minimising deterioration risk across a range of climatic conditions (Figure 7.3), this conservation strategy could also be usefully applied at other earthen sites in addition to Suoyang.

8.6 Theme 4: Future deterioration and potential conservation

The final theme highlighted by the research presented in this thesis addresses the future of earthen heritage. The future of earthen heritage is considered in relation to: (i) the impact of future climate conditions on earthen heritage deterioration; and (ii) the conservation strategies implemented. To fulfil my intention to inform practical conservation (outlined in Section 2.7), a cost-benefit framework, designed using results from this thesis is presented for aiding the conservation decision making process.

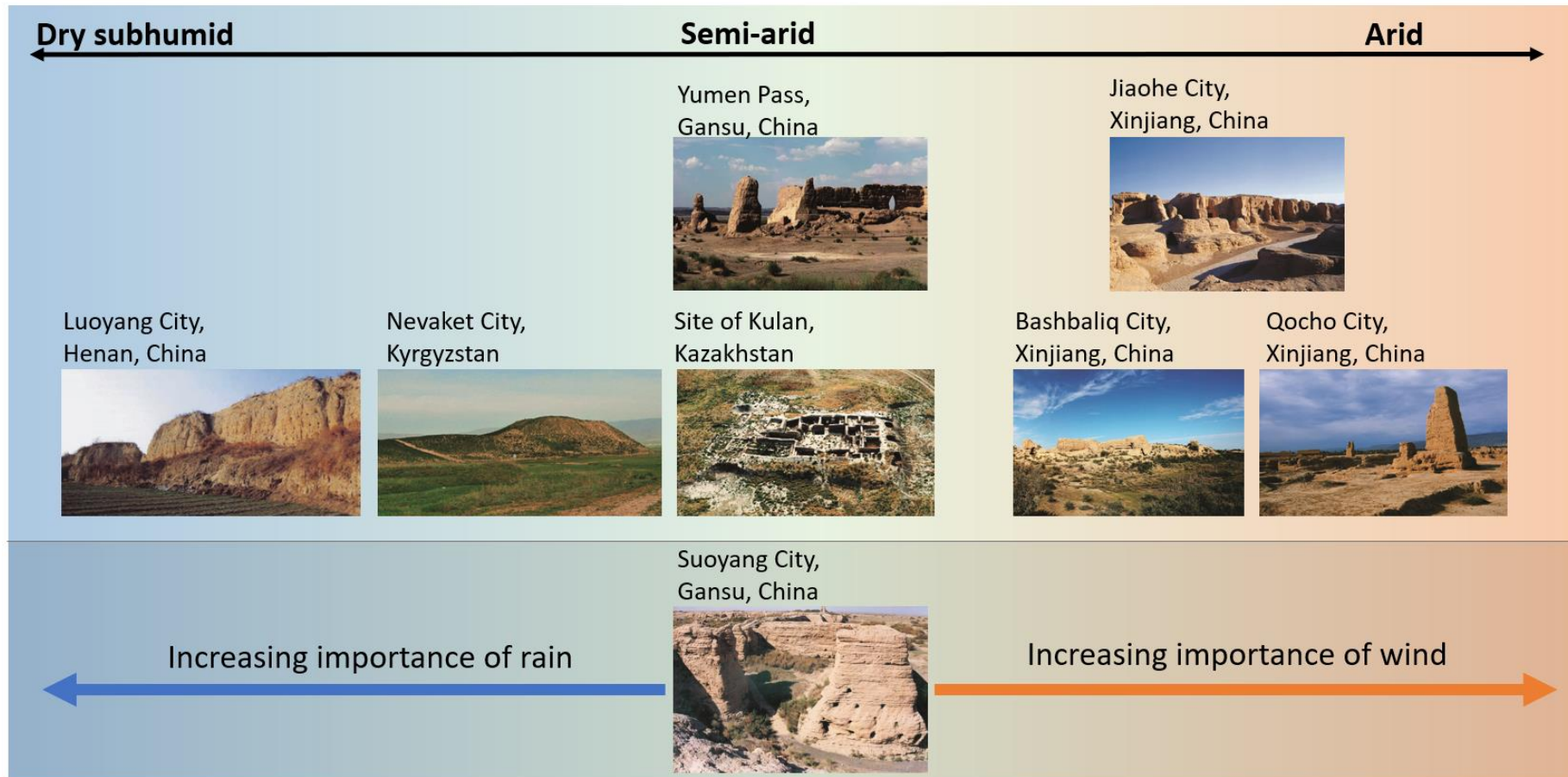


Figure 8.6: The likely importance of wind and rain as drivers of earthen heritage deterioration at sites which form the Silk Roads World Heritage listing, located over a spectrum of dryland climates from dry subhumid to arid. Photo Credits UNSECO (2014).

8.6.1 *Climatic impact*

Future climatic conditions will impact the extent of future deterioration. Even small changes in future windspeed of 1 ms^{-1} could cause notable differences in deterioration risk (Chapter 7, Paper 4; Figure 7.2). The importance of small differences in climatic regimes was seen on the historic walls at Suoyang where there were substantial differences in the types and severity of deterioration features depending on the microclimate of the wall (Chapter 5, Paper 2; Table 5.2). For example, the east inner city wall, exposed to the easterly prevailing wind, had the most severe turreting, while the middle and west inner city walls that are parallel to, but sheltered by, the east inner city wall had notably less severe turreting (Figure 5.6). This suggests that if future windspeeds increased so that the middle and west inner city walls were exposed the windspeeds currently experienced by the east inner city wall, these walls could also become vulnerable to similar severe forms of deterioration, such as turreting.

The importance of considering the interactions between multiple environmental processes under future climate scenarios is also highlighted (Chapters 4 and 7; Papers 1 and 4). For example, future increases in the magnitude of wind events could cause increases in the volume of material loss and spatial coverage associated with wind driven deterioration features (Chapter 4, Paper 1; Figure 4.6). However, increases in windspeed caused greater rates of sediment transport resulting in the formation of larger dunes up the wall face (Figure 7.2). These dunes may act as a protective layer on the covered areas of the wall (Section 7.2) and furthermore might add value to the site by making it seem older and more abandoned than if the site was presented in a sterile format (Woolfitt, 2007). This erosive, as well as protective nature, of the same driver

emphasises the importance of considering earthen heritage deterioration as a complex system with multiple interacting processes. Without this, key interactions and feedbacks between environmental processes, such as the dune formations, that might have a substantial impact on deterioration could be overlooked.

8.6.2 Conservation impact

As well as future climatic conditions, the future condition of earthen heritage will also depend on the conservation strategies implemented (Table 2.3). Of the strategies considered in this thesis, increasing natural vegetation coverage was the most effective strategy for reducing deterioration risk (Chapter 7, Paper 4, Figure 7.2). Results of the visual deterioration survey support this approach: walls surrounded by denser patches of vegetation had notably less severe deterioration (Chapter 5, Paper 2; Figure 5.6). This provides at least an initial indication that increasing natural vegetation is likely to minimise deterioration risk when applied in the field.

However, the decision to implement a conservation strategy is commonly a trade-off between the strategy's ability to minimise deterioration risk and other factors, such as implementation and maintenance costs and the size and aesthetic impact of the strategy (Figure 2.2; Richards et al., 2018). To address these trade-offs, I suggest a four-stage schematic framework for making informed decisions on the relative benefits/trade-off of implementing conservation strategies at sites such as Suoyang (Figure 8.7).

Stage 1

Field data collection:

Deterioration assessment and evaluation of heritage values

Stage 2

Decision strategy for conservation options:

	Climate condition	Conservation options			Conservation outcome sensitive to climate scenario?
		Windbreak	Increase natural vegetation	Do nothing	
Minimise risk of polishing	Low extreme	Footprint	DDR Cheapest	-	DDR = No Cheapest = No Footprint = No
	High extreme	Footprint	DDR Cheapest	-	
Minimise risk of pitting	Low extreme	Footprint	DDR Cheapest	-	DDR = No Cheapest = No Footprint = Yes
	High extreme	-	DDR Cheapest Footprint	-	
Minimise risk of slurry	Low extreme	DDR Footprint	Cheapest	-	DDR = Yes Cheapest = Yes Footprint = Yes
	High extreme	-	-	DDR Cheapest Footprint	
Minimise risk of overall deterioration	Low extreme	Footprint	DDR Cheapest	-	DDR = No Cheapest = No Footprint = Yes
	High extreme	-	DDR Cheapest Footprint	-	

Key:

DDR = Strategy that provides the greatest Decrease in Deterioration Risk

Cheapest = The cheapest strategy that minimises the risk of deterioration to some extent

Footprint = The strategy that has the smallest installation footprint on the site while minimising the risk of deterioration to some extent

Stage 3

Field tests:

Comprehensive testing of strategy at heritage site

Passes field tests?

Yes

No

Stage 4

Implementation:

Chosen conservation strategy implemented at the site with ongoing monitoring of deterioration

Figure 8.7: A schematic showing a four-stage approach to assessing the relative benefits and trade-offs when implementing conservation strategies.

Stage 1 highlights the need for field data to establish the extent of deterioration (e.g. findings from Chapter 5; Paper 2) and heritage values of a site (e.g. Richards et al. (2018); Appendix B) (Figure 8.7).

Stage 2 considers the relative benefits or trade-offs associated with implementing a given conservation strategy. Here we consider:

- (i) a shrub windbreak (5m tall, 30 m upwind);
- (ii) increasing natural vegetation coverage to 80%; or
- (iii) doing nothing,

under low extreme (wind: 1 ms⁻¹ below average; rain 10% below average) or high extreme (wind: 5 ms⁻¹ above average; rain 50% above average) future climate scenarios (Figure 8.7). For a conservation strategy to be selected within the framework it has to reduce the risk of deterioration *to some extent*. If this condition is met, its relative benefits would be assessed by a further three factors:

- 1) the ability for a strategy to cause the *greatest* decrease in deterioration risk (Figure 8.7: 'DDR'), assessed using the risk deterioration results from ViSTA-HD (Table 8.2);
- 2) the relative cost of implementing and maintaining a strategy (Figure 8.7: 'Cheapest'), calculated for the model space in ViSTA-HD using the implementation and maintenance cost breakdowns provided by the Chinese Forestry Partnership for undertaking best practices for land degradation control in dryland areas of China (Table 8.2) (PRC-GEF Partnership, 2008);

- 3) the smallest relative footprint, or area of land required for a strategy (Figure 8.7: Footprint), based on the spatial area of the implemented strategy in the ViSTA-HD model (Table 8.2).

By combining the risk of deterioration under future climate scenarios (Figure 7.3) with trade off factors for the conservation strategies (Table 8.2), increasing natural vegetation cover to 80% is shown to be the strategy that causes the greatest reduction in deterioration risk and also is the cheapest strategy, irrespective of whether future climatic changes cause a low or high extreme scenario to occur (Figure 8.7).

Table 8.2: Trade-off factors for conservation strategies based on the ViSTA-HD model domain used in Chapter 7 (Paper 4).

Conservation strategy	Description	Extent of decrease in deterioration risk	Relative cost	Relative footprint
Windbreak	Shrub-based windbreak as preferred by the Chinese Forestry Partnership. Requires irrigation.	Variable but generally some decrease	Double vegetation cover cost	<1/15 th of the vegetation cover footprint
Vegetation coverage	Hand sowing seeds of species tolerant to low moisture.	Variable but generally greatest decrease	Half the windbreak cost	>15 times the windbreak footprint
Do nothing	No interventions	Variable but generally limited change	No capital input required	No additional space required

Under low extreme conditions, the shrub windbreak has the smallest footprint while still reducing all forms of deterioration but under high extreme conditions 80% vegetation cover was the only one of the strategies tested that minimised deterioration risk and so, even though it has a relatively large footprint, it is the *de facto* smallest footprint available for an effective strategy. Therefore, this suggests that unless it is essential for the conservation strategy to have a small footprint, increasing vegetation cover to 80% is likely to be the most suitable conservation strategy for minimising deterioration regardless of future climatic changes. It should be noted, that this increase in vegetation

should ideally be achieved using species native to the area to minimise the risk of unforeseen consequences caused by introducing new species to a site (e.g. invasion of vegetation).

Stage three of the framework in Figure 8.7 requires field tests using the chosen conservation strategy to be carried out before implementation. As suggested in Section 7.6.5, this would ideally be undertaken over a minimum of one year. This would help ensure the desired impact on deterioration can be achieved, without any unforeseen consequences arising (e.g. attracting pests to the site or altering the height of the water table; Li et al., 2013), before applying it to an entire site.

If the field tests produce the desired reductions in deterioration, stage four kickstarts the implementation of the conservation strategy (Figure 8.7). As this framework is iterative, ongoing monitoring of environmental processes at, and deterioration condition of, the site enables the impact of these strategies to be assessed and for them to be adjusted if required.

8.7 Original contributions of this research

The research presented in this thesis has made a number of original contributions as outlined below.

8.7.1 *Understanding environmental drivers of deterioration at earthen heritage sites*

My research highlights the importance of wind as a driver of deterioration at heritage sites in dryland regions that have structural elements constructed from rammed earth. I have shown that the high frequency occurrence of wind events in dryland regions means

that even though individual wind events have a low magnitude in comparison to rain storm events, they have a substantial cumulative impact on deterioration processes.

8.7.2 The development of field approaches to assess deterioration processes

My research used an innovative range of field methods to assess the process(es) and extent of earthen heritage deterioration, combining low- and high- tech approaches on test and historic walls. My approach shows that by combining multiple methods, challenges faced in the field (e.g. only being able to take non-destructive measurements from the historic walls) can be successfully negotiated. Furthermore, in this work, I show how seemingly simple methods (e.g. visual observations) can be undertaken in a manner that allows for semi-quantitative comparisons between survey sites, and how cutting-edge technology can be applied to earthen heritage research to improve our understanding of deterioration processes.

8.7.3 The development of a cellular automata model for predicting the risk of earthen heritage deterioration

In this thesis, I developed a cellular automata model that is able to capture the risk of earthen heritage deterioration under multiple climate scenarios. This development enables us, and other researchers, to study: (i) the potential risks posed by climate change scenarios; and (ii) the effectiveness of potential conservation scenarios over time periods not feasible in the field. Furthermore, by modelling future deterioration risks, I was also able to show that no strategy is a silver bullet solution for conservation. Instead, choosing a conservation strategy requires undertaking a cost/benefit assessment that is dependent on how a strategy addresses the specific needs and values of a given site. By showing that no future climate or conservation scenario is free from

deterioration risk, my work also supports the need for contemporary definitions of conservation that stress the need for sustainable management of change rather than preserving sites as they currently are.

8.7.4 Evidence based recommendations for nature-based conservation at earthen heritage sites

In this thesis, I demonstrate an evidence-based, site-specific approach for the recommendation of nature-based conservation strategies at earthen heritage sites. This helps address the desire of heritage experts based in both China and the UK to implement conservation strategies that: (i) are applied to the environment rather than the earthen material; and (ii) in a manner that enables a quantitative comparison between potential options. Given the potential for nature-based conservation strategies to minimise deterioration, my research highlights an urgent need for further research into potential unintended consequences caused by these strategies (e.g. altering the water table; increasing the number of rodents in the area). The success of the combined field-based and modelling approach used in the thesis suggests that this approach could similarly be utilised to study the extent to which unintended consequences may pose a problem.

8.7.5 Wider application of research approach

My approach taken in this thesis could also contribute to research studying other types of landform development. This could be particularly applicable for landforms made from earthen materials (e.g. yardangs) and those formed from complex, interacting processes (e.g. rock cliffs). In addition, this approach would be usefully applied to other forms of built heritage (e.g. heritage structures built with stone), enabling key processes of

deterioration to be assessed in the field informing model development, which could assess processes over spatial and/or temporal scales not feasible in the field or laboratory.

8.8 Implications for conservation practice

I aimed to determine the likely impacts of the main environmental drivers of earthen heritage deterioration under current and future conditions in dryland regions to contribute to the field of earthen heritage research by examining the complex interactions between the environment and earthen material and to help inform conservation practice (Section 2.7). My research addressing the four main objective in this thesis, as well as the emergence of four cross cutting themes (Figure 8.1), has shown the importance of wind as a high frequency, low magnitude driver of earthen heritage deterioration under both current and future conditions. In particular, I argue that wind is an important initiator of deterioration, as well as having a significant cumulative deteriorative effect on walls exposed to the prevailing wind direction (Chapter 5, Paper 2; Table 5.3).

My findings therefore imply that conservation strategies for earthen heritage sites in dryland regions need to minimise the impact of wind on earthen heritage. This could be achieved by modifying the environmental conditions around earthen heritage sites using nature-based approaches highlighted in Chapter 7 (Paper 4), such as increasing natural vegetation cover or with the installation of a windbreak.

My findings also suggest that conservation practitioners could also use ViSTA-HD as a decision-making tool helping to assess the trade-offs associated potential nature-based

conservation strategies (Figure 8.7). The design of ViSTA-HD means it can be freely used due to ViSTA-HD's open source code and programming software, flexibility of initial input conditions and relatively low computational cost. As such, it has the potential to help inform conservation strategies at multiple earthen heritage sites in dryland regions of north-west China and Central Asia.

Finally, my results imply that ongoing monitoring of any conservation strategy needs to be designed and undertaken in a manner than captures the impact of high frequency, low magnitude deterioration events. This could be achieved using a range of high- or low-tech methods, such as those used in this thesis over a period of months to years.

8.9 Future work

Future work should aim to improve our understanding of the interactions between environmental processes and their ability to drive deterioration. In particular, future research should:

1) Refine/establish deterioration thresholds for environmental drivers.

Understanding the magnitude and frequency of environmental conditions needed for the formation of specific deterioration features would enable us to:

- (i) better predict the deteriorative impact of future environmental conditions;
- and (ii) improve our ability to use deterioration features as a tool to infer past environmental conditions. For example, further tests exposing earthen materials to windspeeds lower than 12 ms^{-1} should be undertaken to quantify the threshold for wind driven deterioration. If winds of, say, 8 ms^{-1} are found to cause deterioration, this should be incorporated within the environmental risk matrices in ViSTA-HD.

2) Investigate the influence of interacting deterioration processes.

The layering of deterioration features seen on the historic walls at Suoyang, such as polishing occurring over slurry, suggest that the deterioration features caused by past environmental processes can influence subsequent deterioration processes. The extent to which these deterioration legacies significantly impact future deterioration needs further quantification.

3) Quantify the loss of historic material experienced at earthen heritage sites.

Quantifying the loss of historic material would enable topographical changes to earthen heritage sites to be captured over multiple time periods, improving our understanding of the development of deterioration features including larger scale features such as wall slumping and turreting.

Such future research could be undertaken by:

- 1) developing **controlled laboratory experiments** that expose test walls to individual drivers of deterioration at various magnitudes, as well as subjecting test walls to regimes that combine two or more drivers of deterioration.
- 2) carrying out **fieldwork** that provides detailed characterisation of the layering of deterioration features using surface profile characteristics and field-based studies of the development of natural features.
- 3) performing **material characterisation** of historic earthen samples to assess how drivers of deterioration change material properties.
- 4) developing a **quantitative model** of deterioration at earthen sites that captures changes in the topography of earthen structures.

8.10 Conclusions

Many earthen heritage sites are currently experiencing extensive deterioration driven by environmental processes. To pass these sites on to future generations, we urgently need to design and implement effective conservation strategies that: minimise deterioration caused by the main drivers of deterioration; while also respecting a site's heritage value.

In previous research, the role of wind has often been alluded to without substantial consideration. This has likely been caused by: the low magnitude of individual wind events; the small volume of material loss associated with wind-driven deterioration; and the low persistence of wind-driven deterioration features. However, deterioration processes occurring on test and historic walls at the site of Suoyang have shown that the high-frequency nature of wind events mean that wind: (i) is an important initiator of deterioration across the site; and (ii) causes extensive wind-driven deterioration features on walls exposed to the prevailing wind. Given the similarity of Suoyang's material properties, climate and history to other earthen heritage sites in dryland areas of northwest China and central Asia, these findings regarding the importance of wind as a driver of earthen heritage deterioration are likely to be broadly applicable to many other sites in the region.

This importance of understanding wind's role in earthen heritage deterioration was made clear when modelling the future risk of deterioration under a range of potential climatic scenarios. Increasing natural vegetation cover was found to minimise the risk of wind-driven deterioration and, using a framework that addressed trade-off decisions for implementing conservation strategies, was also found to be the cheapest strategy to implement.

This thesis argues for the importance of wind as a driver of earthen heritage deterioration. This finding presents many challenges: it raises methodological and processes-based questions about the methods that should be used to best capture the impact of wind-drive deterioration, and the interactions between wind and other environmental conditions that drive deterioration.

However, it also highlights many opportunities for earthen heritage sites. By understanding the role of wind, conservation strategies can be implemented using nature-based approaches that minimise the risk of future wind-driven deterioration. While these strategies will never completely remove the risk of deterioration, the implementation of such strategies is likely to minimise the risk of environmentally-driven deterioration, while also fulfilling the conservation preferences of heritage experts based in the UK and China.

References



- Agnew, N., Maekawa, S., Coffman, R., Meyer, J., 1996. Evaluation of the performance of a lightweight modular site shelter: Quantitative meteorological data and protective indices for the 'hexashelter.' *Conserv. Manag. Archaeol. Sites* 1, 139–150.
- Agnew, N., Selwitz, C., Demas, M., 2004. Reburial research: preliminary field experiments at Fort Selden. *Conserv. Manag. Archaeol. Sites* 6, 333–345.
- Albero, S., Giavarini, C., Santarelli, M.L., Vodret, A., 2004. CFD modeling for the conservation of the Gilded Vault Hall in the Domus Aurea. *J. Cult. Herit.* 5, 197–203.
- Allen, E.J., 2019. An SDE model for deterioration of rock surfaces. *Stoch. Anal. Appl.* 37, 1012–1027.
- Alva, A., Chiari, G., 1995. Protection and conservation of excavated structures of mudbrick. In: Stanley-Price, N. (Ed.), *Conservation on Archaeological Excavations, with Particular Reference to the Mediterranean Area*. Centre for the Study of the Preservation and Restoration of Cultural Property. ICCROM, Rome, pp. 101–112.
- Alves, D.S., Escada, M.I.S., Pereira, J.L.G., De Albuquerque Linhares, C., 2003. Land use intensification and abandonment in Rondônia, Brazilian Amazônia. *Int. J. Remote Sens.* 24, 899–903.
- Anderson, R.S., Sørensen, M., Willetts, B.B., 1991. A review of recent progress in our understanding of aeolian sediment transport. In: Barndorff-Nielsen, O.E., Willetts, B.B. (Eds.), *Aeolian Grain Transport 1. Acta Mechanica Supplementum, Vol 1*. Springer, Vienna, pp. 1–19.
- Angulo-Ibáñez, Q., 2017. Performance analysis of wooden reinforcement in rammed earth walls. *Period. Polytech. Civ. Eng.* 61, 882–888.

- Arens, S.M., van Boxel, J.H., Abuodha, J.O.Z., 2002. Changes in grain size of sand in transport over a foredune. *Earth Surf. Process. Landforms* 27, 1163–1175.
- Arrigoni, A., Pelosato, R., Dotelli, G., Beckett, C.T.S., Ciancio, D., 2017. Weathering's beneficial effect on waste-stabilised rammed earth: a chemical and microstructural investigation. *Constr. Build. Mater.* 140, 157–166.
- Arrigoni, A., Simoni, G., Dotelli, G., Pelosato, R., Caruso, M., 2019. Rammed Earth stabilised with waste materials: a sustainable and resistant solution. *IOP Conf. Ser. Earth Environ. Sci.* 296, 012019.
- Arslan, M.E., Emiroğlu, M., Yalama, A., 2017. Structural behavior of rammed earth walls under lateral cyclic loading: A comparative experimental study. *Constr. Build. Mater.* 133, 433–442.
- Aslan, Z., 1997. Protective structures for the conservation and presentation of archaeological sites. *J. Conserv. Museum Stud.* 3, 16–20.
- Avrami, E., Guillaud, H., 2008. Introduction. In: Avrami, E., Guillaud, H., Hardy, M. (Eds.), *Terra Literature Review, An Overview of Research in Earthen Architecture Conservation*. The Getty Conservation Institute, Los Angeles.
- Avrami, E., Mason, R., Torre, M.D.L., 2000. Values and heritage conservation, Research Report. Los Angeles, CA.
- Baas, A.C.W., 2002. Chaos, fractals and self-organization in coastal geomorphology: simulating dune landscapes in vegetated environments. *Geomorphology* 48, 309–328.
- Baas, A.C.W., Nield, J.M., 2007. Modelling vegetated dune landscapes. *Geophys. Res.*

Lett. 34, L06405.

Baas, A.C.W., Nield, J.M., 2010. Ecogeomorphic state variables and phase-space construction for quantifying the evolution of vegetated aeolian landscapes. *Earth Surf. Process. Landforms* 35, 717–731.

Bagnold, R.A., 1941. *The physics of blown sand and desert dunes*. Methuen & Co. Ltd, London.

Bailey, R.M., 2010. Spatial and temporal signatures of fragility and threshold proximity in modelled semi-arid vegetation. *Proc. R. Soc. London B Biol. Sci.* 278, 1064–1071.

Bailey, R.M., Thomas, D.S.G., 2014. A quantitative approach to understanding dated dune stratigraphies. *Earth Surf. Process. Landforms* 39, 614–631.

Bakadi, F., Rouai, M., Dekayir, A., Benyassine, E.M., 2020. Degradation Study of an Earthen Historical Rampart of Meknes City (Morocco) Using Ultrasonic Non-destructive Testing. In: Duc Long, P., Dung, N. (Eds.), *Geotechnics for Sustainable Infrastructure Development. Lecture Notes in Civil Engineering*, Vol 62. Springer, Singapore, pp. 1267–1273.

Balderrama, A.A., 2001. The conservation of earthen architecture. *Conserv. Getty Conserv. Inst. Newsl.* 16, 4–11.

Balzter, H., Braun, P.W., Köhler, W., 1998. Cellular automata models for vegetation dynamics. *Ecol. Modell.* 107, 113–125.

Barchyn, T.E., Hugenholtz, C.H., 2015. Yardang evolution from maturity to demise. *Geophys. Res. Lett.* 42, 5865–5871.

- Barnard, H., Wendrich, W.Z., Winkels, A., Bos, J.E.M.F., Simpson, B.L., Cappers, R.T.J.,
2016. The preservation of exposed mudbrick architecture in Karanis (Kom Aushim),
Egypt. *J. F. Archaeol.* 41, 84–100.
- Barnas, K., Kania, O., 2019. Earthen Temples. In: *IOP Conference Series: Materials
Science and Engineering*. Institute of Physics Publishing, Singapore.
- Barton, J., 2009. 3D laser scanning and the conservation of earthen architecture: A case
study at the UNESCO World Heritage Site Merv, Turkmenistan. *World Archaeol.* 41,
489–504.
- Baskaran, A., Kashef, A., 1996. Investigation of air flow around buildings using
computational fluid dynamics techniques. *Eng. Struct.* 18, 861–873.
- Beckett, C.T.S., Ciancio, D., 2016. Durability of cement-stabilised rammed earth: a case
study in Western Australia. *Aust. J. Civ. Eng.* 14, 54–62.
- Beckett, C.T.S., Jaquin, P.A., Morel, J.-C., 2020. Weathering the storm: A framework to
assess the resistance of earthen structures to water damage. *Constr. Build. Mater.*
242, 118098.
- Belnap, J., Gillette, D.A., 1997. Disturbance of biological soil crusts: impacts on potential
wind erodibility of sandy desert soils in southeastern Utah. *L. Degrad. Dev.* 8, 355–
362.
- Belnap, J., Gillette, D.A., 1998. Vulnerability of desert biological soil crusts to wind
erosion: the influences of crust development, soil texture, and disturbance. *J. Arid
Environ.* 39, 133–142.
- Belnap, J., Phillips, S.L., Herrick, J.E., Johansen, J.R., 2007. Wind erodibility of soils at Fort

- Irwin, California (Mojave Desert), USA, before and after trampling disturbance: implications for land management. *Earth Surf. Process. Landforms* 32, 75–84.
- Binda, L., Baronio, G., Cantoni, F., Rocca, P., 1995. Full-scale models for the study of repair techniques on brick masonry surfaces. In: Vincenzini, P. (Ed.), *Ceramics in Architecture: Proceedings of the International Symposium on Ceramics in Architecture of the 8th CIMTEC-World Ceramics Congress and Forum on New Materials*. Techna, Faenza, Italy, pp. 453–64.
- Blocken, B., Carmeliet, J., 2004a. Pedestrian Wind Environment around Buildings: Literature Review and Practical Examples. *J. Therm. Envel. Build. Sci.* 28, 107–159.
- Blocken, B., Carmeliet, J., 2004b. A review of wind-driven rain research in building science. *J. Wind Eng. Ind. Aerodyn.* 92, 1079–1130.
- Bond, S., Worthing, D., 2016. *Managing built heritage: The role of cultural values and significance*, Second ed. ed. Wiley Blackwell, Chichester.
- Bonnet, S., Crave, A., 2003. Landscape response to climate change: Insights from experimental modeling and implications for tectonic versus climatic uplift of topography. *Geology* 31, 123–126.
- Bosher, L., Kim, D., Okubo, T., Chmutina, K., Jigyasu, R., 2019. Dealing with multiple hazards and threats on cultural heritage sites: an assessment of 80 case studies. *Disaster Prev. Manag. An Int. J.* 29, 109–128.
- Bourke, M., Brearley, J., Haas, R., Viles, H., 2007. *A Photographic Atlas of Rock Breakdown Features in Geomorphic Environments*. Planetary Science Institute, Tuscon, Arizona, USA.

- Bourke, M., Viles, H., Nicoli, J., Lyew-Ayee, P., Ghent, R., Holmlund, J., 2008. Innovative applications of laser scanning and rapid prototype printing to rock breakdown experiments. *Earth Surf. Process. Landforms* 33, 1614–1621.
- Brabec, E., Chilton, E., 2015. Toward an ecology of cultural heritage. *Chang. Over Time* 5, 266–285.
- Brimblecombe, P., Bonazza, A., Brooks, N., Grossi, C., Harris, I., Sabbioni, C., 2011. Impact of climate change on earthen buildings. In: Rainer, L., Rivera, A.B., Gandreau, D. (Eds.), *Terra 2008: The 10th International Conference on the Study and Conservation of Earthen Architecture*. Getty Publications, Los Angeles, pp. 278–282.
- Brimblecombe, P., Grossi, C.M., Harris, I., 2010. Climate change critical to cultural heritage. In: Gökçekus, H., Türker, U., LaMoreaux, J. (Eds.), *Survival and Sustainability. Environmental Earth Sciences*. Springer, Berlin, Heidelberg, pp. 387–393.
- Brooks, G., 2002. The ICOMOS International Cultural Tourism Charter: Linking cultural heritage conservation to the celebration of cultural diversity. Principios, practicas y perspectivas. 13th ICOMOS General Assembly and Scientific Symposium. Actas. In: *Estrategias Relativas Al Patrimonio Cultural Mundial. La Salvaguarda En Un Mundo Globalizado*. Pri. Comité Nacional Español del ICOMOS, Madrid, Spain, pp. 308–310.
- Brown, P.W., Robbins, C.R., Clifton, J.R., 1979. ADOBE II: Factors affecting the durability of adobe structures. *Stud. Conserv.* 24, 23–39.
- Brown, R.B., Sandoval, B., M., H.O., 1990. The protection and conservation of the adobe

- structures at Paquimé, Casas Grandes, Chihuahua, Mexico. In: Grimstad, K. (Ed.), 6th International Conference on the Conservation of Earthen Architecture: Adobe 90 Preprints: Las Cruces, New Mexico, U.S.A., October 14–19, 1990. Getty Conservation, Marina del Rey, CA, pp. 204–208.
- Bruno, A., Bultinck, G., Chiari, G., Trossarelli, C., 1968. Contributions to the study of the preservation of mud-brick structures. *Mesopotamia III-IV III–IV*, 445–479.
- Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. *Trans. Inst. Br. Geogr.* 4, 403–484.
- Buckland, C.E., Bailey, R.M., Thomas, D.S.G., 2018. Identifying chronostratigraphic breaks in aeolian sediment profiles using near-surface luminescence dating and changepoint analysis. *Quat. Geochronol.* 46, 45–58.
- Buckland, C.E., Bailey, R.M., Thomas, D.S.G., 2019. Using artificial neural networks to predict future dryland responses to human and climate disturbances. *Sci. Rep.* 9, 3855.
- Bui, Q.-B., Bui, T.T., El-Nabouch, R., Thai, D.K., 2019. Vertical Rods as a Seismic Reinforcement Technique for Rammed Earth Walls: An Assessment. *Adv. Civ. Eng.* in press.
- Bui, Q.-B., Hans, S., Morel, J.-C., Mollion, V., 2011. Influence of water on the mechanical characteristics of rammed-earth material. *WIT Trans. Built Environ.* 118, 565–576.
- Bui, Q.-B., Morel, J.-C., 2009. Assessing the anisotropy of rammed earth. *Constr. Build. Mater.* 23, 3005–3011.
- Bui, Q.-B., Morel, J.-C., Bui, Quoc-Bao, Morel, J.-C., 2015. First Exploratory Study on the

- Ageing of Rammed Earth Material. *Materials (Basel)*. 8, 1–15.
- Bui, Q.-B., Morel, J.C., Hans, S., Walker, P., 2014. Effect of moisture content on the mechanical characteristics of rammed earth. *Constr. Build. Mater.* 54, 163–169.
- Bui, Q.-B., Morel, J.C., Reddy, B.V.V., Ghayad, W., 2009. Durability of rammed earth walls exposed for 20 years to natural weathering. *Build. Environ.* 44, 912–919.
- Bui, T.-T., Bui, Q.-B., Limam, A., Maximilien, S., 2014. Failure of rammed earth walls: From observations to quantifications. *Constr. Build. Mater.* 51, 295–302.
- Bui, T.L., Bui, T.T., Bui, Q.B., Nguyen, X.H., Limam, A., 2020. Out-of-plane behavior of rammed earth walls under seismic loading: Finite element simulation. *Structures* 24, 191–208.
- Bui, T.T., Bui, Q.B., Limam, A., Morel, J.C., 2016. Modeling rammed earth wall using discrete element method. *Contin. Mech. Thermodyn.* 28, 523–538.
- Bull, W.B., 1977. The alluvial-fan environment. *Prog. Phys. Geogr. Earth Environ.* 1, 222–270.
- Campiani, A., Lingle, A., Lercari, N., 2019. Spatial analysis and heritage conservation: Leveraging 3-D data and GIS for monitoring earthen architecture. *J. Cult. Herit.* 39, 166–176.
- Cao, S., Sun, G., Zhang, Z., Chen, L., Feng, Q., Fu, B., McNulty, S., Shankman, D., Tang, J., Wang, Y., Wei, X., 2011. Greening China naturally. *Ambio* 40, 828–831.
- Caperton, T., 1990. Fort Selden Ruins Conservation. In: Grimstad, K. (Ed.), 6th International Conference on the Conservation of Earthen Architecture: Adobe 90

Preprints. Getty Conservation Institute, Los Angeles, pp. 209–211.

Caperton, T.J., 1993. Long term preservation issues related to earthen archaeological sites. In: Seventh International Conference on the Study and Conservation of Earthen Architecture. DGEMN, Silves, p. 324.

Chaudhry, C., Sikka, S., 2009. Conservation treatments for earthen structures in the Western Himalayas of India. APT Bull. 40, 35–42.

Chiari, G., 1990. Chemical surface treatments and capping techniques of earthen structures: A long-term evaluation. In: Grimstad, K. (Ed.), 6th International Conference on the Conservation of Earthen Architecture: Adobe 90 Preprints. The Getty Institute, Los Angeles, pp. 267–273.

Chiari, G., Burger, R., Salazar-Burger, L., 2000. Treatment of an adobe painted frieze in Cardal, Peru, and its evaluation after 12 years. Terra 2000 8th Int. Conf. Study Conserv. Earthen Archit. Prepr. 216–217.

Christensen, J.H., Krishna Kumar, K., Aldrian, E., An, S.-I., Cavalcanti, I.F.A., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J.K., Kitoh, A., Kossin, J., Lau, N.-C., Renwick, J., Stephenson, D.B., S.-P., X., Zhou, T., 2013. Climate Phenomena and their Relevance for Future Regional Climate Change. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., V., B., P.M., M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

- Ciantia, M.O., Castellanza, R., 2016. Modelling weathering effects on the mechanical behaviour of rocks. *Eur. J. Environ. Civ. Eng.* 20, 1054–1082.
- Cigna, F., Tapete, D., 2018. Tracking Human-Induced Landscape Disturbance at the Nasca Lines UNESCO World Heritage Site in Peru with COSMO-SkyMed InSAR. *Remote Sens.* 10, 572.
- Clifton, J.R., 1977. Preservation of Historic Adobe Structures: A Status Report., NBS Technical Note 934. Washington, DC.
- Cooke, L., 2008. Approaches to the conservation and management of earthen architecture in archaeological contexts. Doctoral thesis. University of London.
- Cooke, R.U., Warren, A., Goudie, A., Cooke, R.U., 1993. Desert geomorphology. UCL Press, London.
- Corgnati, S.P., Perino, M., 2013. CFD application to optimise the ventilation strategy of Senate Room at Palazzo Madama in Turin (Italy). *J. Cult. Herit.* 14, 62–69.
- Cornelis, W.M., Gabriels, D., 2005. Optimal windbreak design for wind-erosion control. *J. Arid Environ.* 61, 315–332.
- Correia, M., Guerrero, L., 2018. Conservation of Earthen Building Materials. In: *The Encyclopedia of Archaeological Sciences*. John Wiley & Sons, Inc., Hoboken, NJ, USA, pp. 1–6.
- Correia, M., Guerrero, L., Crosby, A., 2015. Technical strategies for conservation of Earthen archaeological architecture. *Conserv. Manag. Archaeol. Sites* 17, 224–256.
- Coulthard, T.J., Macklin, M.G., Kirkby, M.J., 2002. A cellular model of Holocene upland

- river basin and alluvial fan evolution. *Earth Surf. Process. Landforms* 27, 269–288.
- Crosby, A., 1983. Common sources of deterioration. In: Garrison, J.W., Ruffner, E.F. (Eds.), *Adobe, Practical and Technical Aspects of Adobe Conservation*. Heritage Foundation of Arizona, Prescott, AZ, pp. 13–18.
- Cuadra, C., Karkee, M.B., Tokeshi, K., 2008. Earthquake risk to Inca's historical constructions in Machupicchu. *Adv. Eng. Softw.* 39, 336–345.
- Cui, K., Chen, W., Zhang, J.-K., Bin, H., Zhu, Y.-P., 2012. Study on mechanism of degradation and feature of ancient building materials-rammed earth in arid region. *Sichuan Daxue Xuebao (Gongcheng Kexue Ban)/Journal Sichuan Univ. (Engineering Sci. Ed.* 44, 47-54 [in Chinese].
- Cui, K., Du, Y., Zhang, Y., Wu, G., Yu, L., 2019a. An evaluation system for the development of scaling off at earthen sites in arid areas in NW China. *Herit. Sci.* 7, 14.
- Cui, K., Guan, X.P., Chen, W.W., Chen, M.M., Han, W.F., 2017. Effects of salinized deterioration and aeolian ullage on soils in undercutting areas of earthen ruins in arid regions. *Yantu Gongcheng Xuebao/Chinese J. Geotech. Eng.* 39, 1777-1784 [in Chinese].
- Cui, K., Wu, G., Du, Y., An, X., Wang, Z., 2019b. The coupling effects of freeze-thaw cycles and salinization due to snowfall on the rammed earth used in historical freeze-thaw cycles relics in northwest China. *Cold Reg. Sci. Technol.* 160, 288–299.
- Cui, S., Yang, X., Guo, X., Lin, T., Zhao, Q., Feng, L., 2011. Increased challenges for world heritage protection as a result of urbanisation in Lijiang City. *Int. J. Sustain. Dev.*

- World Ecol. 18, 480–485.
- D’Agostino, D., Congedo, P.M., Cataldo, R., 2014. Computational fluid dynamics (CFD) modeling of microclimate for salts crystallization control and artworks conservation. *J. Cult. Herit.* 15, 448–457.
- Daniel, G., 1970. Neolithic burial mounds. *Nature* 228, 945–946.
- Daoudi, L., Rocha, F., Costa, C., Arrebei, N., Fagel, N., 2018. Characterization of rammed-earth materials from the XVIth century Badii Palace in Marrakech, Morocco to ensure authentic and reliable restoration. *Geoarchaeology* 33, 529–541.
- De La Torre, M., 2013. Values and Heritage Conservation. *Herit. Soc.* 6, 155–166.
- Deng, Y., Gou, X., Gao, L., Yang, M., Zhang, F., 2017. Tree-ring recorded moisture variations over the past millennium in the Hexi Corridor, northwest China. *Environ. Earth Sci.* 76, 272.
- Dillehay, T.D., 1990. Mapuche ceremonial landscape, social recruitment and resource rights. *World Archaeol.* 22, 223–241.
- Domínguez Martínez, O., García Hermida, A., Moreno Adán, C., 2014. Stratigraphic analysis of earthen architecture: The mosque of m’hamid el ghizlane. In: Mileto, C., Vegas, F., García Soriano, L., Cristini, V. (Eds.), *Earthen Architecture: Past, Present and Future*. CRC Press, London, pp. 127–132.
- Dong, Z., Liu, X., Wang, H., Wang, X., 2003. Aeolian sand transport: a wind tunnel model. *Sediment. Geol.* 161, 71–83.
- Dong, Z., Lv, P., Lu, J., Qian, G., Zhang, Z., Luo, W., 2012. Geomorphology and origin of

- Yardangs in the Kumtagh Desert, Northwest China. *Geomorphology* 139–140, 145–154.
- Douglas-Jones, R., Hughes, J.J., Jones, S., Yarrow, T., 2016. Science, value and material decay in the conservation of historic environments. *J. Cult. Herit.* 21, 823–833.
- Du, Y., Chen, W., Cui, K., Gong, S., Pu, T., Fu, X., 2017. A Model Characterizing Deterioration at Earthen Sites of the Ming Great Wall in Qinghai Province, China. *Soil Mech. Found. Eng.* 53, 426–434.
- Duguay, Y., Bernier, M., Lévesque, E., Tremblay, B., 2014. Monitoring of subarctic shrub vegetation characteristics using TerraSAR-X and RADARSAT-2 data. In: *International Geoscience and Remote Sensing Symposium (IGARSS)*. Institute of Electrical and Electronics Engineers Inc., pp. 1194–1197.
- Dunkerley, D.L., 1997. Banded vegetation: Survival under drought and grazing pressure based on a simple cellular automaton model. *J. Arid Environ.* 35, 419–428.
- Dupont, S., Bergametti, G., Marticorena, B., Simoëns, S., 2013. Modeling saltation intermittency. *J. Geophys. Res. Atmos.* 118, 7109–7128.
- Dutta, M., Husain, Z., 2009. An application of Multicriteria Decision Making to built heritage. The case of Calcutta. *J. Cult. Herit.* 10, 237–243.
- E, Y., Wang, J., Gao, S., Yan, P., Yang, Z., 2007. Monitoring of vegetation changes using multi-temporal NDVI in peripheral regions around Minqin Oasis, Northwest China. In: *International Geoscience and Remote Sensing Symposium (IGARSS)*. pp. 3448–3451.
- Ehlmann, B.L., Viles, H.A., Bourke, M.C., 2008. Quantitative morphologic analysis of

- boulder shape and surface texture to infer environmental history: A case study of rock breakdown at the Ephrata Fan, Channeled Scabland, Washington. *J. Geophys. Res. Earth Surf.* 113, F02012.
- Eldridge, D.J., Leys, J.F., 2003. Exploring some relationships between biological soil crusts, soil aggregation and wind erosion. *J. Arid Environ.* 53, 457–466.
- Elert, K., Bel-Anzué, P., Monasterio-Guillot, L., Pardo, S., 2019. Performance of alkaline activation for the consolidation of earthen architecture. *J. Cult. Herit.* 39, 93–102.
- Elert, K., Pardo, E.S., Rodriguez-Navarro, C., 2015. Alkaline activation as an alternative method for the consolidation of earthen architecture. *J. Cult. Herit.* 16, 461–469.
- Elert, K., Sebastián, E., Valverde, I., Rodriguez-Navarro, C., 2008. Alkaline treatment of clay minerals from the Alhambra Formation: Implications for the conservation of earthen architecture. *Appl. Clay Sci.* 39, 122–132.
- English Heritage, 2008. *Conservation Principles, Policies and Guidance*. London.
- Eriksen, A.M., Gregory, D.J., Villa, C., Lynnerup, N., Botfeldt, K.B., Rasmussen, A.R., 2016. The effects of wood anisotropy on the mode of attack by the woodborer *Teredo navalis* and the implications for underwater cultural heritage. *Int. Biodeterior. Biodegradation* 107, 117–122.
- Erkal, A., D'Ayala, D., Sequeira, L., 2012. Assessment of wind-driven rain impact, related surface erosion and surface strength reduction of historic building materials. *Build. Environ.* 57, 336–348.
- Evans, R., 1998. The erosional impacts of grazing animals. *Prog. Phys. Geogr. Earth Environ.* 22, 251–268.

- Fagone, M., Kloft, H., Loccarini, F., Ranocchiai, G., 2019. Jute fabric as a reinforcement for rammed earth structures. *Compos. Part B Eng.* 175, 107064.
- Faria, P., Silva, V., Pereira, C., Rocha, M., 2012. The monitoring of rammed earth experimental walls and characterization of rammed earth samples. In: *Rammed Earth Conservation - Proceedings of the 1st International Conference on Rammed Earth Conservation, RESTAPIA 2012*. Valencia; Spain; 21 - 23 June 2012, pp. 91–97.
- Ferretti, V., Bottero, M., Mondini, G., 2014. Decision making and cultural heritage: An application of the Multi-Attribute Value Theory for the reuse of historical buildings. *J. Cult. Herit.* 15, 644–655.
- Fodde, E., 2009. Traditional earthen building techniques in central Asia. *Int. J. Archit. Herit.* 3, 145–168.
- Fodde, E., Khan, M.S., 2013. Affordable Monsoon Rain Mitigation Measures In The World Heritage Site Of Moenjodaro, Pakistan. *Int. J. Archit. Heritage.* 11, 161–173.
- Ford, M., Watson, L., El Kadi, H., 1997. Developing a conservation strategy for earthen buildings. In: *International Series on Advances in Architecture*. Computational Mechanics Publications, Southampton, pp. 213–219.
- Forster, A.M., Thomson, D.S., Richards, K., Pilcher, N., Vettese, S., 2018. Western and Eastern building conservation philosophies: perspectives on permanence and impermanence. *Int. J. Archit. Herit.* 13, 870–885.
- Fredheim, L.H., Khalaf, M., 2016. The significance of values: heritage value typologies re-examined. *Int. J. Herit. Stud.* 22, 466–481.
- Fujii, Y., Fodde, E., Watanabe, K., Murakami, K., 2009. Digital photogrammetry for the

documentation of structural damage in earthen archaeological sites: The case of Ajina Tapa, Tajikistan. *Eng. Geol.* 105, 124–133.

Gamrani, N., R'kha Chaham, K., Ibnoussina, M., Fratini, F., Rovero, L., Tonietti, U., Mansori, M., Daoudi, L., Favotto, C., Youbi, N., 2012. The particular “rammed earth” of the Saadian sugar refinery of Chichaoua (XVIth century, Morocco): Mineralogical, chemical and mechanical characteristics. *Environ. Earth Sci.* 66, 129–140.

Gao, X., Shi, Y., Zhang, D., Giorgi, F., 2012. Climate change in China in the 21st century as simulated by a high resolution regional climate model. *Chinese Sci. Bull.* 57, 1188–1195.

Gares, P.A., Jackson, D.W.T., Davidson-Arnott, R.G.D., Nordstrom, K.F., Bauer, B.O., Sherman, D.J., Carter, R.W.G., 1996. Alongshore variations in aeolian sediment transport: Carrick Finn Strand, Ireland. *J. Coast. Res.* 12, 673–682.

Garvey, B., Castro, I.P., Wiggs, G., Bullard, J., 2005. Measurements of Flows Over Isolated Valleys. *Boundary-Layer Meteorol.* 117, 417–446.

Gomes, M.I., Faria, P., Gonçalves, T.D., 2019. Rammed earth walls repair by earth-based mortars: The adequacy to assess effectiveness. *Constr. Build. Mater.* 205, 213–231.

Gomes, M.I., Gonçalves, T.D., Faria, P., 2014. Unstabilized rammed earth: Characterization of material collected from old constructions in south portugal and comparison to normative requirements. *Int. J. Archit. Herit.* 8, 185–212.

Gomes, M.I., Gonçalves, T.D., Faria, P., 2016. Hydric behavior of earth materials and the effects of their stabilization with cement or lime: Study on repair mortars for historical rammed earth structures. *J. Mater. Civ. Eng.* 28, 04016041.

- Goossens, D., Offer, Z.Y., 2000. Wind tunnel and field calibration of six aeolian dust samplers. *Atmos. Environ.* 34, 1043–1057.
- Goudie, A., Stokes, S., Cook, J., Samieh, S., El-Rashidi, O.A., 1999. Yardang landforms from Kharga Oasis, south-western Egypt. In: *Zeitschrift Fur Geomorphologie, Supplementband*. pp. 97–112.
- Goudie, A., Viles, H.A., 2010. *Landscapes and geomorphology: a very short introduction, Very short introductions*. Oxford University Press, Oxford.
- Goudie, A.S., Viles, H.A., 1999. The frequency and magnitude concept in relation to rock weathering. *Zeitschrift für Geomorphol. Suppl.* Vol. 175–189.
- Grau-Bové, J., Mazzei, L., Thickett, D., Strlič, M., 2019. New Perspectives on the Study of Particulate Matter Deposition within Historic Interiors. *Stud. Conserv.* 64, 193–202.
- Grau-Bové, J., Strlič, M., Mazzei, L., 2016. Applicability of a drift-flux model of aerosol deposition in a test tunnel and an indoor heritage environment. *Build. Environ.* 106, 78–90.
- Greeley, R., Iversen, J.D., 1985. *Wind as a geological process : on Earth, Mars, Venus, and Titan*, Cambridge planetary science series. Cambridge University Press, Cambridge.
- Greenley, R., Blumberg, D.G., Williams, S.H., 1996. Field measurements of the flux and speed of wind-blown sand. *Sedimentology* 43, 41–52.
- Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W.M., Railsback, S.F., Thulke, H.-H., Weiner, J., Wiegand, T., DeAngelis, D.L., 2005. Pattern-oriented modeling of agent-based complex systems: Lessons from ecology. *Science* (80-.). 310, 987–991.

- Guerrero, L., 2002. Deterioration of heritage built in adobe. *Diseño y Soc.* 13, 4–11.
- Guillaud, H., 2008. Characterization of Earthen Materials. In: Avrami, E., Guillaud, H., Hardy, M. (Eds.), *Terra Literature Review: An Overview of Research in Earthen Architecture Conservation*. Getty Conservation Institute, Los Angeles, CA.
- Guo, J., Huang, G., Wang, X., Li, Y., Lin, Q., 2017. Investigating future precipitation changes over China through a high-resolution regional climate model ensemble. *Earth's Futur.* 5, 285–303.
- Guo, J., Huang, G., Wang, X., Li, Y., Yang, L., 2018. Future changes in precipitation extremes over China projected by a regional climate model ensemble. *Atmos. Environ.* 188, 142–156.
- Gutierrez-Carrillo, M.L., Arizzi, A., Bestué Cardiel, I., Sebastián Pardo, E., 2019. Study of the State of Conservation and the Building Materials Used in Defensive Constructions in South-Eastern Spain: The Example of Mula Castle in Murcia. *Int. J. Archit. Herit.* in press.
- Gutiérrez-Elorza, M., Desir, G., Gutiérrez-Santolalla, F., 2002. Yardangs in the semiarid central sector of the Ebro Depression (NE Spain). *Geomorphology* 44, 155–170.
- Gyssels, G., Poesen, J., Bochet, E., Li, Y., 2005. Impact of plant roots on the resistance of soils to erosion by water: a review. *Prog. Phys. Geogr. Earth Environ.* 29, 189–217.
- Haines-Young, R.H., Petch, J.R., 1983. Multiple Working Hypotheses: Equifinality and the Study of Landforms. *Trans. Inst. Br. Geogr.* 8, 458.
- Hamard, E., Cammas, C., Fabbri, A., Razakamanantsoa, A., Cazacliu, B., Morel, J.C., 2017. Historical Rammed Earth Process Description Thanks to Micromorphological

- Analysis. *Int. J. Archit. Herit.* 11, 314–323.
- Han, F., Yang, Z., Shi, H., Liu, Q., Wall, G., 2016. How to Promote Sustainable Relationships between Heritage Conservation and Community, Based on a Survey. *Sustainability* 8, 886–896.
- Hanazato, T., Niitsu, Y., Morii, M., Minowa, C., Nitto, K., Yokoo, T., 2016. Seismic and wind performance of five-storied pagoda of timber heritage structure affected by Great East Japan Earthquake of 2011 and typhoon Jelawat of 2012. In: *Structural Analysis of Historical Constructions: Anamnesis, Diagnosis, Therapy, Controls - Proceedings of the 10th International Conference on Structural Analysis of Historical Constructions, SAHC 2016*. CRC Press/Balkema, pp. 1343–1348.
- Harris, C., Rea, B., Davies, M., 2001. Scaled physical modelling of mass movement processes on thawing slopes. *Permafr. Periglac. Process.* 12, 125–135.
- Harrison, R., 2013. Forgetting to remember, remembering to forget: late modern heritage practices, sustainability and the ‘crisis’ of accumulation of the past. *Int. J. Herit. Stud.* 19, 579–595.
- He, C., Zhang, Q., Li, Y., Li, X., Shi, P., 2005. Zoning grassland protection area using remote sensing and cellular automata modeling - A case study in Xilingol steppe grassland in northern China. *J. Arid Environ.* 63, 814–826.
- Heisler, G.M., Dewalle, D.R., 1988. Effects of windbreak structure on wind flow. *Agric. Ecosyst. Environ.* 22–23, 41–69.
- Historic England, 2015. *Practical building conservation: Earth, Brick and Terracotta*. Ashgate Publishing Limited, Farnham.

Houben, H., Balderrama, A.A., Simon, S., 2004. Our earthen architectural heritage:

Materials research and conservation. *MRS Bull.* 25, 338–341.

Hoyle, A.M., 1990. Chan Chan: Aportes para la conservacion dela arquitectura de tierra.

In: 6th International Conference of the Conservation of Earthen Architecture. The Getty Conservation Institute, Los Angeles, CA.

Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., Shinoda, M., Ma, Z., Guo, W., Li, Z., Zhang,

L., Liu, Y., Yu, H., He, Y., Xie, Y., Guan, X., Ji, M., Lin, L., Wang, S., Yan, H., Wang, G.,

2017. Dryland climate change: Recent progress and challenges. *Rev. Geophys.* 55, 719–778.

Huang, J., Yu, H., Guan, X., Wang, G., Guo, R., 2016. Accelerated dryland expansion

under climate change. *Nat. Clim. Chang.* 6, 166–171.

Huang, P., Peng, X., 2015. Experimental study on raindrop splash erosion of Fujian earth

building rammed earth material. *Mater. Res. Innov.* 19, 639–645.

Hughes, R., 1998. A review of works at the world heritage monument of moenjodaro,

Pakistan. In: Corfield, M., Hinton, P., Nixon, T., Pollard, M. (Eds.), *Preserving*

Archaeological Remains in Situ. Museum of London Archaeology Service, London, pp. 26–30.

Hui, P., Tang, J., Wang, S., Niu, X., Zong, P., Dong, X., 2018. Climate change projections

over China using regional climate models forced by two CMIP5 global models. Part II: projections of future climate. *Int. J. Climatol.* 38, 78–94.

Huinink, H.P., Pel, L., Kopinga, K., 2004. Simulating the growth of tafoni. *Earth Surf.*

Process. Landforms 29, 1225–1233.

- Hussaini, S.M.S., Toufigh, V., 2019. Strength and Fracture Behavior of Rammed-Earth Materials. *J. Mater. Civ. Eng.* 31, 04019228.
- ICOMOS China, 2015. *Zhongguo wen wu gu ji bao hu zhun ze* = Principles for the Conservation of Heritage Sites in China. Rev. ed. ICOMOS China, Beijing.
- Illampas, R., Ioannou, I., Charmpis, D.C., 2013. Overview of the Pathology, Repair and Strengthening of Adobe Structures. *Int. J. Archit. Herit.* 7, 165–188.
- Iyer-Raniga, U., Wong, J.P.C., 2012. Evaluation of whole life cycle assessment for heritage buildings in Australia. *Build. Environ.* 47, 138–149.
- Jackson, S., Hitchins, D., Eisner, H., 2010. What Is the Systems Approach? *INSIGHT* 13, 41–43.
- Jaquin, P.A. 2008. Analysis of Historic Rammed Earth Construction. Doctoral Thesis. Durham University.
- Jaquin, P.A. 2012. Influence of Arabic and Chinese Rammed Earth Techniques in the Himalayan Region. *Sustainability.* 4, 2650-2660.
- Jaquin, P.A., Augarde, C.E., Gerrard, C.M., 2008. Chronological Description of the Spatial Development of Rammed Earth Techniques. *Int. J. Archit. Herit.* 2, 377–400.
- Jiang, Y., Luo, Y., Zhao, Z., Shi, Y., Xu, Y., Zhu, J., 2010. Projections of wind changes for 21st century in China by three regional climate models. *Chinese Geogr. Sci.* 20, 226–235.
- Jo, Y.H., Lee, S.M., Lee, C.H., 2018. Material characteristics and building technique for the rammed earth wall of the 13th Korean fortress in Ganghwa. *Environ. Earth Sci.*

77, 617.

Jones, S., 2009. Experiencing Authenticity at Heritage Sites: Some Implications for Heritage Management and Conservation. *Conserv. Manag. Archaeol. Sites* 11, 133–147.

Jun, Z., 2014. Comparison of Heritage Conservation Philosophies in China and Other Countries. In: ICOMOS China (Ed.), *International Principles and Local Practices of Cultural Heritage Conservation*. ICOMOS China, Beijing, pp. 40–61.

Kai, C., Chen, W., Kuang, J., Wang, X.-D., Han, W.-F., 2012. Effect of deterioration of earthen ruin with joint function of salinized and alternating wet and dry in arid and semi-arid regions. *J. Cent. South Univ. Technol.* 43, 2378-2384 [in Chinese].

Kennedy, C.J., 2015. The role of heritage science in conservation philosophy and practice. *Hist. Environ. Policy Pract.* 6, 214–228.

Kenney, W.A., 1987. A method for estimating windbreak porosity using digitized photographic silhouettes. *Agric. For. Meteorol.* 39, 91–94.

Kerner, B.S., Klenov, S.L., Wolf, D.E., 2002. Cellular automata approach to three-phase traffic theory. *J. Phys. A. Math. Gen.* 35, 9971–10013.

Khadka, B., Shakya, M., 2016. Comparative compressive strength of stabilized and unstabilized rammed earth. *Mater. Struct. Constr.* 49, 3945–3955.

Kim, D.S., Park, H.J., 2014. Centrifuge modelling on seismic behaviour of stone architectural heritages. In: *Physical Modelling in Geotechnics - Proceedings of the 8th International Conference on Physical Modelling in Geotechnics 2014, ICPMG 2014*. pp. 47–60.

- Kok, J.F., Parteli, E.J.R., Michaels, T.I., Karam, D.B., 2012. The physics of wind-blown sand and dust. *Reports Prog. Phys.* 75, 106901.
- Kong, W., Sun, O.J., Xu, W., Chen, Y. 2009. Changes in vegetation and landscape patterns with altered river water-flow in arid West China. *J. Arid Envir.* 73, 306-313.
- Koob, S.P., Rogers, M.H., Sams, G.K., 1990. Preserving the eighth-century B. C. Mud brick architecture at Gordion, Turkey: Approaches to conservation. In: Agnew, N. (Ed.), *Proceeding of 6th International Conference on the Conservation of Earthen Architecture*. The Getty Institute, Los Angeles, p. 289.
- Kraus, C., Hirmas, D., Roberts, J., 2013. Microbially indurated rammed earth: A long awaited next phase of earthen architecture. In: *ARCC: The Visibility of Research*. The University of North Carolina, Charlotte, pp. 58–65.
- Kris, N., Van Balen, K., Smars, P., 2001. VIRTHERF, a vision on heritage conservation. In: Thwaites, H., Addison, L. (Eds.), *Proceedings Seventh International Conference on Virtual Systems and Multimedia*. IEEE Comput. Soc, pp. 191–200.
- Kristensen, L., 1998. Cup Anemometer Behavior in Turbulent Environments. *J. Atmos. Ocean. Technol.* 15, 5–17.
- Kuenen, P.H., 1948. Slumping in the Carboniferous rocks of Pembrokeshire. *Q. J. Geol. Soc. London* 104, 365–385.
- Kumaraperumal, A., Baker, P.H., Sanders, C.H., Galbraith, G.H., McLean, R.C., 2006. Comparison of measured and modelled driving rain data on a historic building with standard assessment methods. In: *Proceedings of the 3rd International Building Physics Conference - Research in Building Physics and Building Engineering*. pp.

897–904.

- La Russa, M.F., Rovella, N., Ruffolo, S.A., Scarciglia, F., Macchia, A., Licchelli, M., Malagodi, M., Khalilli, F., Randazzo, L., 2019. Consolidation of earthen building materials: a comparative study. *Archaeol. Anthropol. Sci.* 11, 4643–4652.
- Laity, J.E., 2009. Landforms, landscapes, and processes of aeolian erosion. In: Parsons, A.J., Abrahams, A.D. (Eds.), *Geomorphology of Desert Environments*. Springer, Dordrecht, Netherlands, pp. 597–627.
- Laity, J.E., 2011. Wind Erosion in Drylands. In: *Arid Zone Geomorphology: Process, Form and Change in Drylands*. Wiley Blackwell, pp. 539–568.
- Lancaster, N., 1984. Characteristics and occurrence of wind erosion features in the Namib Desert. *Earth Surf. Process. Landforms* 9, 469–478.
- Lancaster, N., 1995. *Geomorphology of desert dunes*. Routledge, London ; New York.
- Lane, S., 2010. Numerical Modelling in Physical Geography: Understanding, Explanation and prediction. In: Clifford, N.J., Valentine, G. (Eds.), *Key Methods in Geography*. Sage Publications, London, pp. 263–290.
- Lazzari, M., Geraldi, E., Lapenna, V., Loperte, A., 2006. Natural hazards vs human impact: An integrated methodological approach in geomorphological risk assessment on the Tursi historical site, Southern Italy. *Landslides* 3, 275–287.
- Lecun, Y., Bengio, Y., Hinton, G., 2015. Deep learning. *Nature* 521, 436–444.
- Lercari, N., 2019. Monitoring earthen archaeological heritage using multi-temporal terrestrial laser scanning and surface change detection. *J. Cult. Herit.* 39, 152–165.

- Lesschen, J.P., Schoorl, J.M., Cammeraat, L.H., 2009. Modelling runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity. *Geomorphology* 109, 174–183.
- Li, G. S., Qu, J.J., Han, Q.J., Fang, H.Y., Wang, W.F., 2013. Responses of three typical plants to wind erosion in the shrub belts atop Mogao Grottoes, China. *Ecol. Eng.* 57, 293–296.
- Li, G.S., Qu, J.J., Han, Q.J., Fang, H.Y., Wang, W.F., 2013. Responses of three typical plants to wind erosion in the shrub belts atop Mogao Grottoes, China. *Ecol. Eng.* 57, 293–296.
- Li, H., Xie, Y., 2011. On the Formation of Suoyang City Ruins and Related Remains [WWW Document]. *Silk Road*. URL https://web.archive.org/web/20190123125708/http://dh.dha.ac.cn/Journal/Article?id=28026&table=DHXKEYWORDCJFD_METADATA (accessed 2.7.20).
- Li, J., Dong, Z., Qian, G., Zhang, Z., Luo, W., Lu, J., Wang, M., 2016. Yardangs in the Qaidam Basin, northwestern China: Distribution and morphology. *Aeolian Res.* 20, 89–99.
- Li, L., Shao, M., Wang, S., Li, Z., 2011. Preservation of earthen heritage sites on the Silk Road, northwest China from the impact of the environment. *Environ. Earth Sci.* 64, 1625–1639.
- Li, X.-Y., Liu, L.-Y., Wang, J.-H., 2004. Wind tunnel simulation of aeolian sandy soil erodibility under human disturbance. *Geomorphology* 59, 3–11.
- Li, Z., 1990. Consolidation of a Neolithic earthen site with potassium silicate. In:

- Grimstad, K. (Ed.), 6th International Conference on the Conservation of Earthen Architecture: Adobe 90 Preprints. Getty Conservation Institute, Los Angeles, pp. 295–301.
- Li, Z., Wang, X., Sun, M., Chen, W., Guo, Q., Zhang, H., 2011. Conservation of Jiaohe ancient earthen site in China. *J. Rock Mech. Geotech. Eng.* 3, 270–281.
- Liang, Y., 2018. Experimental study on frost resistance of rammed earth building materials. *Chem. Eng. Trans.* 66, 1177–1182.
- Lister, R.H., Lister, F.C., 1987. Aztec Ruins on the Animas, excavated, preserved and interpreted. Western National Parks Association, Tuscon.
- Livingstone, I., 1986. Geomorphological significance of wind flow patterns over a Namib linear dune. In: Nickling, W.G. (Ed.), *Aeolian Geomorphology*. Allen and Unwin, Boston, MA, pp. 97–112.
- Lombillo, I., Villegas, L., Fodde, E., Thomas, C., 2014. In situ mechanical investigation of rammed earth: Calibration of minor destructive testing. *Constr. Build. Mater.* 51, 451–460.
- Loughlin, G.F., 1931. Notes on the weathering of natural building stones. *Am. Soc. Test. Mater.* 3, 759–767.
- Lourenço, P.B., Ciocci, M.P., Greco, F., Karanikoloudis, G., Cancino, C., Torrealva, D., Wong, K., 2019. Traditional techniques for the rehabilitation and protection of historic earthen structures: The seismic retrofitting project. *Int. J. Archit. Herit.* 13, 15–32.
- Lu, Y.M., Chiu, Y.P., Shiau, Y.C., 2018. Study on applying inorganic polymers to restore

- rammed earth brick monuments. *Emerg. Mater. Res.* 7, 200–205.
- Lunt, M.G., 1980. Stabilised soil blocks for building research establishment. *Overseas Build. Notes* 184, 127–144.
- Luo, Y., Yin, B., Peng, X., Xu, Y., Zhang, L., 2019. Wind-rain erosion of Fujian Tulou Hakka Earth Buildings. *Sustain. Cities Soc.* 50, 101666.
- Maniatidis, V. Walker, P. 2003. A Review of Rammed Earth Construction. University of Bath: Bath.
- Mao, X., Zhao, D., Chen, P., Hou, W., 2008. Consolidation experiment on earthen architecture site in arid region. *Yanshilixue Yu Gongcheng Xuebao/Chinese J. Rock Mech. Eng.* 27, 7-11 [in Chinese].
- Mao, X., Zhao, D., Zhang, W., 2015. Experimental study on the effects of wind erosion and reinforcement for the rammed soil. *J. Xi'an Univ. Archit. Technol. Nat. Sci. Ed.* 47, 555-559 [in Chinese].
- Marques, A.R., Lima, L.L., Garcia, Q.S., Atman, A.P.F., 2020. A novel cellular automata approach: seed input/output of the alien species *Leucaena leucocephala* in the soil and the effects of climate changes. *Plant Ecol.* 221, 141–154.
- Martín-del-Río, J.J., Flores-Alés, V., Alejandre-Sánchez, F.J., Blasco-López, F.J., 2019. New Method for Historic Rammed-earth Wall Characterization: The Almohade Ramparts of Malaga and Seville. *Stud. Conserv.* 64, 363–372.
- Matero, F., 1999. Lessons from the Great House: Condition and treatment history as prologue to site conservation and management at Casa Grande Ruins National Monument. *Conserv. Manag. Archaeol. Sites* 3, 203–224.

- Matero, F., 2015. Mud Brick Metaphysics and the Preservation of Earthen Ruins. *Conserv. Manag. Archaeol. Sites* 17, 209–223.
- Matero, F., Moss, E., 2004. Temporary site protection for earthen walls and murals at Çatalhöyük, Turkey. *Conserv. Manag. Archaeol. Sites* 6, 213–227.
- Mateus, L., Veiga, M.R., de Brito, J., Silva, A.S., 2019. Mineralogical and mechanical characterization of rammed earth external renderings of the south of Portugal. *Constr. Build. Mater.* 225, 1160–1169.
- Mayaud, J.R., Bailey, R.M., Wiggs, G.F.S., 2017a. A coupled vegetation/sediment transport model for dryland environments. *J. Geophys. Res. Earth Surf.* 122, 875–900.
- Mayaud, J.R., Bailey, R.M., Wiggs, G.F.S., 2017b. Modelled responses of the Kalahari Desert to 21st century climate and land use change. *Nat. Sci. Reports* 7, 3887.
- Mayaud, J.R., Wiggs, G.F.S., Bailey, R.M., 2016a. Characterizing turbulent wind flow around dryland vegetation. *Earth Surf. Process. Landforms* 41, 1421–1436.
- Mayaud, J.R., Wiggs, G.F.S., Bailey, R.M., 2016b. Dynamics of skimming flow in the wake of a vegetation patch. *Aeolian Res.* 22, 141–151.
- Mayaud, J.R., Wiggs, G.F.S., Bailey, R.M., 2017c. A field-based parameterization of wind flow recovery in the lee of dryland plants. *Earth Surf. Process. Landforms* 42, 378–386.
- Mazar, A., 1999. The conservation and management of mudbrick buildings at Tell Qasile, Israel. *Conserv. Manag. Archaeol. Sites* 3, 103–108.

- McKay, C.P., Molaro, J.L., Marinova, M.M., 2009. High-frequency rock temperature data from hyper-arid desert environments in the Atacama and the Antarctic Dry Valleys and implications for rock weathering. *Geomorphology* 110, 182–187.
- Merritt, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport models. In: *Environmental Modelling and Software*. Elsevier BV, pp. 761–799.
- Messenzehl, K., Meyer, H., Otto, J.C., Hoffmann, T., Dikau, R., 2017. Regional-scale controls on the spatial activity of rockfalls (Turtmann Valley, Swiss Alps) — A multivariate modeling approach. *Geomorphology* 287, 29–45.
- Messenzehl, K., Viles, H., Otto, J.-C., Ewald, A., Dikau, R., 2018. Linking rock weathering, rockwall instability and rockfall supply on talus slopes in glaciated hanging valleys (Swiss Alps). *Permafr. Periglac. Process.* 29, 135–151.
- Miccoli, L., Müller, U., Fontana, P., 2014. Mechanical behaviour of earthen materials: A comparison between earth block masonry, rammed earth and cob. *Constr. Build. Mater.* 61, 327–339.
- Micelli, F., Cascardi, A., 2020. Structural assessment and seismic analysis of a 14th century masonry tower. *Eng. Fail. Anal.* 107, 104198.
- Mohammad, A.G., Adam, M.A., 2010. The impact of vegetative cover type on runoff and soil erosion under different land uses. *Catena* 81, 97–103.
- Mol, L., 2016. Measuring Rock Hardness in the Field. In: Carpenter, M. (Ed.), *The Geoscience Handbook*, . American Geosciences Institute, Alexandria, VA, pp. 438–439.

- Momeni, A., Khanlari, G.R., Heidari, M., Bagheri, R., Bazvand, E., 2015. Assessment of physical weathering effects on granitic ancient monuments, Hamedan, Iran. *Environ. Earth Sci.* 74, 5181–5190.
- Morel, J.C., Bui, Q.-B., Hamard, E., 2012. Weathering and durability of earthen material and structures. In: *Modern Earth Buildings: Materials, Engineering, Constructions and Applications*. Elsevier Ltd, pp. 282–303.
- Mottershead, D.N., 2000. Identification and mapping of rock weathering surface forms and features. *Zeitschrift fur Geomorphol. Suppl.* 120, 5–22.
- Murray, A.B., Paola, C., 1994. A cellular model of braided rivers. *Nature* 371, 54–57.
- Najimi, A.W., 2011. Built heritage in Afghanistan: threats, challenges and conservation. *Int. J. Environ. Stud.* 68, 343–361.
- Narteau, C., Zhang, D., Rozier, O., Claudin, P., 2009. Setting the length and time scales of a cellular automaton dune model from the analysis of superimposed bed forms. *J. Geophys. Res.* 114, F03006.
- Nature Editorial team, 2019. Humboldt’s legacy. *Nat. Ecol. Evol.* 3, 1265–1266.
- Negi, H.S., Kumar, A., Rao, N.N., Thakur, N.K., Shekhar, M.S., Snehmani, 2020. Susceptibility assessment of rainfall induced debris flow zones in Ladakh–Nubra region, Indian Himalaya. *J. Earth Syst. Sci.* 129, 30.
- Newmann, J.V., 2010. The conservation of earthen architectural heritage in seismic areas. In: *Advanced Materials Research*. pp. 65–77.
- Nickling, W.G., Mckenna Neuman, C., 1997. Wind tunnel evaluation of a wedge-shaped

- aeolian sediment trap. *Geomorphology* 18, 333–345.
- Nield, J.M., Baas, A.C.W., 2008a. Investigating parabolic and nebkha dune formation using a cellular automaton modelling approach. *Earth Surf. Process. Landforms* 33, 724–740.
- Nield, J.M., Baas, A.C.W., 2008b. Investigating parabolic and nebkha dune formation using a cellular automaton modelling approach. *Earth Surf. Process. Landforms* 33, 724–740.
- Nield, J.M., Baas, A.C.W., 2008c. The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response. *Glob. Planet. Change* 64, 76–92.
- Nowamooz, H., Chazallon, C., 2011. Finite element modelling of a rammed earth wall. *Constr. Build. Mater.* 25, 2112–2121.
- Okin, G., Gregory, 2016. Should precipitation influence dust emission in global dust models? EGU Gen. Assem. 2016, held 17-22 April. 2016 Vienna Austria, id. EPSC2016-17947 18.
- Oliver, A., 2008. Conservation of earthen archaeological sites. In: Avrami, E.C., Guillaud, H., Hardy, M. (Eds.), *Terra Literature Review: An Overview of Research in Earthen Architecture Conservation*. The Getty Institute, Los Angeles, pp. 80–96.
- Oliver, A., Getty Adobe Project, Getty Conservation Institute, Museum of New Mexico, 2000. Fort Selden adobe test wall project: Phase I: Final report. Los Angeles, CA.
- Oliver, P., 1983. Earth as a building material today. *Oxford Art J.* 5, 31–38.

Orazi, R., 2000. Restoration and Maintenance of the earth and stone walls of Khor Rori.

In: Terra 2000: 8th International Conference on the Study and Conservation of Earthen Architecture. Preprints. Torquay, United Kingdom, 11- 13 May 2000.

English Heritage, London, pp. 86–92.

Oreskes, N., Shrader-Frechette, K., Belitz, K., 1994. Verification, Validation, and

Confirmation of Numerical Models in the Earth Sciences 263, 641–646.

Osanyintola, O.F., Simonson, C.J., 2006. Moisture buffering capacity of hygroscopic

building materials: Experimental facilities and energy impact. *Energy Build.* 38, 1270–1282.

Pan, C., Chen, K., Chen, D., Xi, S., Geng, J., Zhu, D., 2020. Research progress on in-situ

protection status and technology of earthen sites in moisty environment. *Constr. Build. Mater.* 253, 119219.

Papakonstantinou, K.A., Kiranoudis, C.T., Markatos, N.C., 2000. Computational analysis

of thermal comfort: the case of the archaeological museum of Athens. *Appl. Math. Model.* 24, 477–494.

Parracha, J.L., Silva, A.S., Cotrim, M., Faria, P., 2019. Mineralogical and microstructural

characterisation of rammed earth and earthen mortars from 12th century Paderne Castle. *J. Cult. Herit.* 42, 226–239.

Pei, Q., Wang, X., Zhao, L., Zhang, B., Guo, Q., 2020. A sticky rice paste preparation

method for reinforcing earthen heritage sites. *J. Cult. Herit.* in press.

Pei, Q.Q., Wang, X.D., Guo, Q.L., Zhao, L.Y., Zhang, B., Li, Z.P., 2020. Action Mechanism of

Sticky Rice-Paste-Modified Site Soil: A Traditional Chinese Cementitious Material.

- Stud. Conserv. 65, 238–250.
- Pelletier, J.D., Kapp, P.A., Abell, J., Field, J.P., Williams, Z.C., Dorsey, R.J., 2018. Controls on Yardang Development and Morphology: 1. Field Observations and Measurements at Ocotillo Wells, California. *J. Geophys. Res. Earth Surf.* 123, 694–722.
- Pendlebury, J., Short, M., While, A., 2009. Urban World Heritage Sites and the problem of authenticity. *Cities* 26, 349–358.
- Peng, X., Shi, W., Hua, C., 2015. Study on the mechanism and loss of erosion by wind driven rain for rammed earth buildings. *Sichuan Daxue Xuebao (Gongcheng Kexue Ban)/Journal Sichuan Univ. Eng. Sci. Ed.* 47, 105–111 [in Chinese].
- Piscioneri, N., Smyth, T.A.G., Hesp, P.A., 2019. Flow dynamics over a foredune scarp. *Earth Surf. Process. Landforms* 44, 1064–1076.
- Plate, E.J., 1971. The aerodynamics of shelter belts. *Agric. Meteorol.* 8, 203–222.
- PRC-GEF Partnership, 2008. Best Practices for Land Degradation Control in Dryland Areas of China. China Forestry Publishing House, Beijing.
- Pu, T., Chen, W., Du, Y., Li, W., Su, N., 2016a. Snowfall-related deterioration behavior of the Ming Great Wall in the eastern Qinghai-Tibet Plateau. *Nat. Hazards* 84, 1539–1550.
- Pu, T., Chen, W., Lü, H., Du, Y., 2016b. Analysis on function of deterioration of typical earthen ruins under the coupling of salinized and freezing and thawing in Qinghai-Tibet Plateau. *J. Cent. South Univ. Sci. Technol.* 47, 1420–1426 [in Chinese].

- Qian, F., 2007. China's Burra Charter: The Formation and Implementation of the China Principles. *Int. J. Herit. Stud.* 13, 255–264.
- Rainer, L., 2008. Deterioration and pathology of earthen architecture. In: Avrami, E., Guillaud, H., Hardy, M. (Eds.), *Terra Literature Review, An Overview of Research in Earthen Architecture Conservation*. The Getty Conservation Institute, Los Angeles, CA, pp. 45–61.
- Ravankhah, M., Schmidt, M., Will, T., 2017. Multi-hazard disaster risk identification for World Cultural Heritage sites in seismic zones. *J. Cult. Herit. Manag. Sustain. Dev.* 7, 272–289.
- Ravi, S., Zobeck, T.M., Over, T.M., Okin, G.S., D'Odorico, P., 2006. On the effect of moisture bonding forces in air-dry soils on threshold friction velocity of wind erosion. *Sedimentology* 53, 597–609.
- Rehman, A., Shahid, H., Sultan, A., Afzal, M.A., Tahir, M.O., 2019. Deforestation Analysis of Northern Areas(Pakistan) using Image Processing and Maximum Likelihood Supervised Classification. In: *2019 2nd International Conference on Communication, Computing and Digital Systems, C-CODE 2019*. Institute of Electrical and Electronics Engineers Inc., pp. 205–210.
- Rempel, A.W., Rempel, A.R., 2019. Frost Resilience of Stabilized Earth Building Materials. *Geosciences* 9, 328.
- Reyes, J.C., Yamin, L.E., Hassan, W.M., Sandoval, J.D., Gonzalez, C.D., Galvis, F.A., 2018. Shear behavior of adobe and rammed earth walls of heritage structures. *Eng. Struct.* 174, 526–537.

Richards, J., Mayaud, J., Zhan, H., Wu, F., Bailey, R., Viles, H., 2020. Modelling the risk of deterioration at earthen heritage sites in drylands. *Earth Surf. Process. Landforms* Ahead of print.

Richards, J., Orr, S.A., Viles, H., 2019a. Reconceptualising the relationships between heritage and environment within an Earth System Science framework. *J. Cult. Herit. Manag. Sustain. Dev.* 10, 122–129.

Richards, J., Viles, H., Guo, Q., n.d. The importance of wind as a driver of earthen heritage deterioration in dryland environments.

Richards, J., Wang, Y., Orr, S., Viles, H., Wang, Y., Orr, S.A., Viles, H., 2018. Finding Common Ground between United Kingdom Based and Chinese Approaches to Earthen Heritage Conservation. *Sustainability* 10, 3086.

Richards, J., Zhao, G., Zhang, H., Viles, H., 2019b. A controlled field experiment to investigate the deterioration of earthen heritage by wind and rain. *Herit. Sci.* 7, 51.

Richards, P.J., Hoxey, R.P., 2012. Pressures on a cubic building-Part 1: Full-scale results. *Jnl. Wind Eng. Ind. Aerodyn.* 102, 72–86.

Richards, P.J., Hoxey, R.P., Short, L.J., 2001. Wind pressures on a 6 m cube. *J. Wind Eng. Ind. Aerodyn.* 89, 1553–1564.

Rodway-Dyer, S., Ellis, N., 2018. Combining remote sensing and on-site monitoring methods to investigate footpath erosion within a popular recreational heathland environment. *J. Environ. Manage.* 215, 68–78.

Rosado Correia, M.R.A., Walliman, N.S.R., 2014. Defining criteria for intervention in earthen-built heritage conservation. *Int. J. Archit. Herit.* 8, 581–601.

- Rothert, E., Eggers, T., Cassar, J., Ruedrich, J., Fitzner, B., Siegesmund, S., 2007. Stone properties and weathering induced by salt crystallization of Maltese Globigerina Limestone. *Geol. Soc. Spec. Publ.* 271, 189–198.
- Rowell, A.L.K., Thomas, D.S.G., Bailey, R.M., Holmes, P.J., 2018. Sand ramps as palaeoenvironmental archives: Integrating general principles and regional contexts through reanalysis of the Klipkraal Sands, South Africa. *Geomorphology* 311, 103–113.
- Santiago, J.L., Martín, F., Cuerva, A., Bezdeneznykh, N., Sanz-Andrés, A., 2007. Experimental and numerical study of wind flow behind windbreaks. *Atmos. Environ.* 41, 6406–6420.
- Schaffer, R.J., 1932. The weathering of natural building stones. H.M. Stationery Office, London.
- Schmidhuber, J., 2015. Deep Learning in neural networks: An overview. *Neural Networks* 61, 85–117.
- Schumm, S.A., Lichty, R.W., 1965. Time, space, and causality in geomorphology. *Am. J. Sci.* 263, 110–119.
- Schwämmle, V., Herrmann, H.J., 2005. A model of Barchan dunes including lateral shear stress. *Eur. Phys. J. E* 16, 57–65.
- Selwitz, C., 1995. Saving the Fort Selden ruins: The use of a composite blend of chemicals to stabilize fragile historic adobe. *Conserv. Manag. Archaeol. Sites* 1, 109–116.
- Selwitz, C., Coffman, R., Agnew, N., 1990. The getty adobe research project at Fort Selden III: An evaluation of the application of chemical consolidants to test walls. In:

- Agnew, N. (Ed.), *Proceedings of the 6th International Conference on the Conservation of Earthen Architecture*. The Getty Institute, Los Angeles, pp. 255–260.
- Shao, M., Li, L., Wang, S., Wang, E., Li, Z., 2013. Deterioration mechanisms of building materials of Jiaohe ruins in China. *J. Cult. Herit.* 14, 38–44.
- Shen, Y., Chen, W., Kuang, J., Du, W., 2017. Effect of salts on earthen materials deterioration after humidity cycling. *J. Cent. South Univ.* 24, 796-806 [in Chinese].
- Sherman, D.J., Hotta, S., 1990. Aeolian sediment transport: theory and measurement. *Coast. Dunes form Process* 17, 16–37.
- Sherman, D.J., Swann, C., Barron, J.D., 2014. A high-efficiency, low-cost aeolian sand trap. *Aeolian Res.* 13, 31–34.
- Shi, W., Peng, X., Chen, Y., 2014. Erosion measurement of rammed earth wall in the wild. *J. Nat. Disasters* 23, 138–143.
- Shi, Y., Shen, Y., Kang, E., Li, D., Ding, Y., Zhang, G., Hu, R., 2007. Recent and Future Climate Change in Northwest China. *Clim. Change* 80, 379–393.
- Silva, R.A., Domínguez-Martínez, O., Oliveira, D. V., Pereira, E.B., 2018. Comparison of the performance of hydraulic lime- and clay-based grouts in the repair of rammed earth. *Constr. Build. Mater.* 193, 384–394.
- Smith, R., 1991. The application of cellular automata to the erosion of landforms. *Earth Surf. Process. Landforms* 16, 273–281.
- Stoyanov, S., Mason, P., Bailey, C., 2010. Smeared shell modelling approach for

- structural analysis of heritage composite structures – An application to the Cutty Sark conservation. *Comput. Struct.* 88, 649–663.
- Strlič, M., 2015. A brief theory of heritage science [WWW Document]. *Natl. Herit. Sci. Forum*. URL <https://nationalheritagescienceforum.wordpress.com/2015/04/16/a-brief-theory-of-heritage-science-by-professor-matija-strlic-ucl-institute-for-sustainable-heritage/> (accessed 5.13.20).
- Strlič, M., 2018. Heritage Science: A Future-Oriented Cross-Disciplinary Field. *Angew. Chemie - Int. Ed.* 57, 7260–7261.
- Su, M.M., Wall, G., 2012. Global–local relationships and governance issues at the Great Wall World Heritage Site, China. *J. Sustain. Tour.* 20, 1067–1086.
- Sun, B., Zhou, Z.H., Zhang, H.Y., Zhang, Y.X., Zheng, L., 2011. Characteristics and prediction model of surface temperature for rammed earthen architecture Ruins. *Yantu Lixue/Rock Soil Mech.* 32, 867–871.
- Sun, L.-D., Zhang, C.-J., Zhao, H.-Y., Lin, J.-J., Qu, W., 2013. Features of Climate Change in Northwest China during 1961–2010. *Adv. Clim. Chang. Res.* 4, 12–19.
- Tan, L., Zhang, W., Qu, J., Wang, J., An, Z., Li, F., 2016. Aeolian sediment transport over gobi: Field studies atop the Mogao Grottoes, China. *Aeolian Res.* 21, 53–60.
- Taylor, M.R., 1990. An evaluation of the New Mexico State monuments adobe test walls at Fort Selden. In: Agnew, N. (Ed.), *Proceedings of the 6th International Conference on the Conservation of Earthen Architecture*. The Getty Institute, Los Angeles, pp. 383–389.
- Teutonico, J., 2008. Foreward. In: Avrami, E., Guillaud, H., Hardy, M. (Eds.), *Terra*

Literature Review, An Overview of Research in Earthen Architecture Conservation.

The Getty Conservation Institute, Los Angeles.

Thomas, D.S.G., 2011. Arid zone geomorphology : process, form and change in drylands, 3rd ed. ed. Wiley-Blackwell, Chichester.

Thompson, J.P., Coats, T.J., Sims, M.R., 2015. Known knowns, known unknowns, and unknown unknowns: can systems medicine provide a new approach to sepsis? *BJA Br. J. Anaesth.* 114, 874–877.

Thornbush, M., Viles, H., 2005. The changing façade of magdalen college, Oxford: Reconstructing long-term soiling patterns from archival photographs and traffic records. *J. Archit. Conserv.* 11, 40–57.

Tian, Q., Gou, X., Zhang, Y., Peng, J., Wang, J., Chen, T., 2007. Tree-Ring Based Drought Reconstruction (A.D. 1855–2001) for the Qilian Mountains, Northwestern China. *Tree-Ring Res.* 63, 27–36.

Torita, H., Satou, H., 2007. Relationship between shelterbelt structure and mean wind reduction. *Agric. For. Meteorol.* 145, 186–194.

Torraca, G., Chirari, G., Gullini, G., 1972. Report on Mud Brick Preservation. *Mesopotamia* 7, 259–287.

Tsoar, H., 1983. Wind tunnel modeling of echo and climbing dunes. *Dev. Sedimentol.* 38, 247–259.

Turkington, A. V., Martin, E., Viles, H.A., Smith, B.J., 2003. Surface change and decay of sandstone samples exposed to a polluted urban atmosphere over a six-year period: Belfast, Northern Ireland. *Build. Environ.* 38, 1205–1216.

- Twiss, K.C., 2007. The Neolithic of the Southern Levant. *Evol. Anthropol.* 16, 24–35.
- Tyson, S., 1999. Sand ramps or climbing dunes? Identification and palaeoenvironmental significance of aeolian deposits in the southern Kalahari and Breede River Valley, South Africa. University of Cape Town.
- UNESCO, 2014. Silk Roads: Initial Section of the Silk Roads, the Routes Network of Tianshan Corridor. Nomination Document.
- UNESCO, 2016. The Site of Suoyang City Introduction [WWW Document]. Silk Roads World Herit. Site. URL <http://www.silkroads.org.cn/article-1121-1.html> (accessed 2.7.20).
- UNESCO, 2017. 2015-2017 Conservation Report of Silk Roads: the Routes Network of Chang'an–Tianshan Corridor, China Section.
- Van Boxel, J.H., Sterk, G., Arens, S.M., 2004. Sonic anemometers in aeolian sediment transport research. *Geomorphology* 59, 131–147.
- Vega, E., Montaña, C., 2011. Effects of overgrazing and rainfall variability on the dynamics of semiarid banded vegetation patterns: A simulation study with cellular automata. *J. Arid Environ.* 75, 70–77.
- Velde, B., 2008. Formation of earthen materials. In: Avrami, E., Hubert, G., Hardy, M. (Eds.), *Terra Literature Review: An Overview of Research in Earthen Architecture Conservation*. The Getty Conservation Institute, Los Angeles, pp. 15–20.
- Viles, H.A., 2001. Scale issues in weathering studies. *Geomorphology* 41, 63–72.
- Viles, H.A., Goudie, A.S., 2007. Rapid salt weathering in the coastal Namib desert:

- Implications for landscape development. *Geomorphology* 85, 49–62.
- Viles, H.A., Goudie, A.S., 2013. Weathering in the central Namib Desert, Namibia: Controls, processes and implications. *J. Arid Environ.* 93, 20–29.
- Wang, B., Zhang, M., Wei, J., Wang, S., Li, Xiaofei, Li, S., Zhao, A., Li, Xiaoshou, Fan, J., 2013. Changes in extreme precipitation over Northeast China, 1960 - 2011. *Quat. Int.* 298, 177–186.
- Wang, L., Chen, W., 2014. A CMIP5 multimodel projection of future temperature, precipitation, and climatological drought in China. *Int. J. Climatol.* 34, 2059–2078.
- Wang, R., Cheng, Q., Liu, L., Yan, C., Huang, G., Wang, R., Cheng, Q., Liu, L., Yan, C., Huang, G., 2019. Multi-Model Projections of Climate Change in Different RCP Scenarios in an Arid Inland Region, Northwest China. *Water* 11, 347.
- Wang, X., Guo, Q., Fan, Y., Yang, S., Zhang, P., 2015. Multi-field coupling equipment for research on the weathering mechanism of rock and earthen relics. *Dunhuang Res.* 5, 103–110.
- Wang, X., Guo, Q., Yang, S., Zhang, D., Wang, Y., 2016. Nondestructive testing and assessment of consolidation effects of earthen sites. *J. Rock Mech. Geotech. Eng.* 8, 726–733.
- Wang, X., Li, Z., Zhang, L., 2010. Condition, Conservation, and Reinforcement of the Yumen Pass and Hecang Earthen Ruins near Dunhuang. In: Agnew, N. (Ed.), *Conservation of Ancient Sites on the Silk Road: Proceedings of the Second International Conference on the Conservation of Grotto Sites, Mogao Grottoes, Dunhuang, People's Republic of China*. Getty Conservation Institute, Los Angeles,

CA, pp. 351–357.

Wang, X., Pei, Q., Guo, Q., Li, Z., Wang, Y., Zhao, J., 2019. Stress mechanism for the rammed layer interfaces of earthen heritage sites with different treatments. *J. Cult. Herit.* 39, 110–119.

Wang, X., Zhang, B., Pei, Q., Guo, Q., Chen, W., Li, F., 2020. Experimental studies on sacrificial layer in conservation of earthen sites. *J. Cult. Herit.* 41, 74–83.

Wang, X.D., Zhang, H.Y., Yan, G.S., Pei, Q.Q., 2010. Durability of Ancient Earthen Architecture under Wind Erosion in the Milan Ancient City along the Silk Road of China. *Adv. Mater. Res.* 163–167, 3230–3236.

Ward, A.W., Greeley, R., 1984. Evolution of the yardangs at Rogers Lake, California. *Bull. Geol. Soc. Am.* 95, 829–837.

Warren, J., 1999. Conservation of Earth Structures, Conservation of Earth Structures. Butterworth-Heinemann, Michigan.

Wasson, R.J., Hyde, R., 1983. Factors determining desert dune type. *Nature* 304, 337–339.

Webster, F.A., 2008. Earthen Structures: Assessing Seismic Damage, Performance, and Interventions. In: Avrami, E., Guillaud, H., Hardy, M. (Eds.), *Terra Literature Review*. The Getty Conservation Institute, Los Angeles, pp. 69–79.

WHEAP, 2012. World Heritage: Inventory of earthen architecture.

Wiggs, G.F.S., Bullard, J.E., Garvey, B., Castro, I., 2002. Interactions Between Airflow and Valley Topography with Implications for Aeolian Sediment Transport. *Phys. Geogr.*

23, 366–380.

Wilhelm, K., Viles, H., Burke, Ó., 2016. Low impact surface hardness testing (Equotip) on porous surfaces - advances in methodology with implications for rock weathering and stone deterioration research. *Earth Surf. Process. Landforms* 41, 1027–1038.

Williams, G., 1964. Some Aspects of the Eolian Saltation Load. *Sedimentology* 3, 257–287.

Williams, J., 2009. The Role of Science in the Management of the UK's Heritage. National Heritage Science Strategy, Bristol.

Winter, T., 2014. Beyond Eurocentrism? Heritage conservation and the politics of difference. *Int. J. Herit. Stud.* 20, 123–137.

Wolfe, S.A., Nickling, W.G., 1993. The protective role of sparse vegetation in wind erosion. *Prog. Phys. Geogr.* 17, 50–68.

Wolff, C., Plessen, B., Dudashvili, A.S., Breitenbach, S.F., Cheng, H., Edwards, L.R., Strecker, M.R., 2017. Precipitation evolution of Central Asia during the last 5000 years. *The Holocene* 27, 142–154.

Wolfram, S., 1984. Universality and complexity in cellular automata. *Phys. D Nonlinear Phenom.* 10, 1–35.

Woolfitt, C., 2007. Preventive conservation of ruins: reconstruction, reburial and enclosure. In: Ashurst, J. (Ed.), *Conservation of Ruins*. Butterworth–Heinemann, Oxford, pp. 147–194.

World Congress TERRA, 2016. TERRA 2016 Draft Recommendations [WWW Document].

URL

https://terra2016.sciencesconf.org/conference/terra2016/pages/2016_07_14_Recommendations_DRAFT.pdf (accessed 3.26.20).

Wright, J.S., 2002. Geomorphology and stone conservation: Sandstone decay in Stoke-on-Trent. *Struct. Surv.* 20, 50–61.

Wu, R., Peng, X., Zhang, L., 2012. Influence of water contents on shear strength of rammed earth wall of earth-building. In: *Advanced Materials Research*. pp. 172–175.

Xie, Y., Ward, R., Fang, C., Qiao, B., 2007a. The urban system in West China: A case study along the mid- section of the ancient Silk Road – He-Xi Corridor. *Cities* 24, 60–73.

Xie, Y., Ward, R., Fang, C., Qiao, B., 2007b. The urban system in West China: A case study along the mid-section of the ancient Silk Road - He-Xi Corridor. *Cities* 24, 60–73.

Xiong, Y., Xin, X., Kou, X., 2019. Simulation and Projection of Near-Surface Wind Speeds in China by BCC-CSM Models. *J. Meteorol. Res.* 33, 149–158.

Xu, H., Wan, X., Fan, X., 2014. Rethinking authenticity in the implementation of China's heritage conservation: the case of Hongcun Village. *Tour. Geogr.* 16, 799–811.

Xu, X., Zheng, F., Wilson, G. V., Wu, M., 2017. Upslope inflow, hillslope gradient and rainfall intensity impacts on ephemeral gully erosion. *L. Degrad. Dev.* 28, 2623–2635.

Yang, B., Qin, C., Bräuning, A., Burchardt, I., Liu, J., 2011. Rainfall history for the Hexi Corridor in the arid northwest China during the past 620 years derived from tree rings. *Int. J. Climatol.* 31, 1166–1176.

- Young, W., Brandis, K., Kingsford, R., 2006. Modelling monthly streamflows in two Australian dryland rivers: Matching model complexity to spatial scale and data availability. *J. Hydrol.* 331, 242–256.
- Yuan, P.B., Dai, P.F., Chen, W.W., 2016. Enzyme induced calcite precipitation (EICP) to strengthen the ability of anti-wind erosion of earthen archaeological sites. In: *Ancient Underground Opening and Preservation - Proceedings of the International Symposium on Scientific Problems and Long-Term Preservation of Large-Scale Ancient Underground Engineering*, 2015. pp. 327–330.
- Zhang, D., Narteau, C., Rozier, O., 2010. Morphodynamics of barchan and transverse dunes using a cellular automaton model. *J. Geophys. Res.* 115, F03041.
- Zhang, H.-Y., Liu, P., Wang, J.-F., Wang, X.-D., 2009. Generation and detachment of surface crust on ancient earthen architectures. *Soil Mech.* 7598, 1883–1891.
- Zhang, H., Yang, L., Liu, P., Chen, Y., Zhang, G., 2018. Study on Thermal Deterioration Simulation Test of Superficial Layer on Rammed Earthen Ruins. *Hunan Daxue Xuebao/Journal Hunan Univ. Nat. Sci.* 45, 149-156 [in Chinese].
- Zhang, H., Zhu, S., Li, M., Zhang, X., 2016. Water Repellency of Monument Soil Treated by Tung Oil. *Geotech. Geol. Eng.* 34, 205–216.
- Zhang, J., Chen, P., Chen, W., Li, Z., Wang, N., Zhang, S., 2015. Anchor performance of wood bolt fully grouted by natural hydraulic lime and quartz sand slurry. *Tumu Jianzhu yu Huanjing Gongcheng/Journal Civil, Archit. Environ. Eng.* 37, 86-93 [in Chinese].
- Zhang, J., Li, Z., Chen, W., Wang, X., Guo, Q., Wang, N., 2017a. Pull-out behaviour of

- wood bolt fully grouted by PS-F slurry in rammed earth heritages. *Geomech. Geoengin.* 12, 279–290.
- Zhang, J., Li, Z., Chen, W., Wang, X., Sun, M., Guo, Q., 2017b. The properties of potassium silicate/ fly ash slurry used in the conservation of adobe structures. *Stud. Conserv.* 62, 114–121.
- Zhang, K., Tan, P., Ma, G., Cao, P., 2016. Modeling of the progressive failure of an overhang slope subject to differential weathering in Three Gorges Reservoir, China. *Landslides* 13, 1303–1313.
- Zhang, P., Cheng, H., Edwards, R.L., Chen, F., Wang, Y., Yang, X., Liu, Jian, Tan, M., Wang, X., Liu, Jinghua, An, C., Dai, Z., Zhou, J., Zhang, D., Jia, J., Jin, L., Johnson, K.R., 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science* 322, 940–942.
- Zhang, X., Xie, Y. 2017. Detecting historical vegetation changes in the Dunhuang oasis protected area using Landsat images. *Sustainability*. 9, 1780.
- Zhang, Y., Ye, W.M., Chen, B., Chen, Y.G., Ye, B., 2016. Desiccation of NaCl-contaminated soil of earthen heritages in the Site of Yar City, northwest China. *Appl. Clay Sci.* 124–125, 1–10.
- Zhao, D., Lu, W., Wang, Y., Mao, X., Ai, Y., Jiang, H., 2016. Experimental studies on earthen architecture sites consolidated with BS materials in arid regions. *Adv. Mater. Sci. Eng.* 2016, 6836315.
- Zhao, J., Broms, B.B., Zhou, Y., Choa, V., 1994. A study of the weathering of the bukit timah granite part a: Review, field observations and geophysical survey. *Bull. Int.*

Assoc. Eng. Geol. - Bull. l'Association Int. Géologie l'Ingénieur 49, 97–106.

Zhao, T., Zhang, H., Yan, G., Ping, L., 2012. Geotechnical approach to earthen architecture durability by cyclic freeze and thaw test. *Electron. J. Geotech. Eng.* 17 C, 263–276.

Zhou, B., Wen, Q.H., Xu, Y., Song, L., Zhang, X., 2014. Projected changes in temperature and precipitation extremes in China by the CMIP5 multimodel ensembles. *J. Clim.* 27, 6591–6611.

Zhou, L., 2008. Thirty Years of Chinese Cultural Heritage Protection. *Conserv. Archit. Herit.* 12, 1–5.

Zhou, T., Liu, B., 2019. Experimental study on the shaking table tests of a modern inner-reinforced rammed earth structure. *Constr. Build. Mater.* 203, 567–578.

Zhu, C.-H., Li, N., Guo, B.-X., Liu, Q.-P., 2018. Defect detection of an ancient building with brick-clay structure base. *Yantu Gongcheng Xuebao/Chinese J. Geotech. Eng.* 40, 169-176 [in Chinese].

Zhu, G., 2012. China's architectural heritage conservation movement. *Front. Archit. Res.* 1, 10–22.

Zhu, Y., 2015. Cultural effects of authenticity: contested heritage practices in China. *Int. J. Herit. Stud.* 21, 594–608.

Appendices



Appendix A: Author contribution

The vast majority of work complete in this thesis is my own. As all four submitted papers were co-authored, both my own contribution (underlined) and the contribution of the co-authors is outlined below.

Paper 1 (Chapter 4)

J. Richards and H. Viles conceptualized the study. The data collection was designed and undertaken by J. Richards, G. Zhao and H. Zhang. The data was analysed and visualised by G. Zhao and J. Richards. Funding acquisition was sort by H. Viles and H. Viles supervised the project. J. Richards wrote the original draft with J. Richards, H. Viles, G. Zhao and H. Zhang reviewing and editing the manuscript.

Paper 2 (Chapter 5)

This study was conceptualised and designed by J. Richards and H.Viles. The work was able to be undertaken with the support of Q.Guo. Data analysis was undertaken by J. Richards with guidance from H. Viles. The writing and editing were undertaken by J. Richards and H. Viles. All authors read and approved the final version of the manuscript.

Paper 3 (Chapter 6)

J. Richards, J. Mayaud and H. Viles conceived of the function of model. J. Richards, J. Mayaud, R. Bailey and H. Viles contributed to model development. J. Richards, H. Zhan and F. Wu collected the field data used to build the model. J. Richards, J. Mayaud, R. Bailey and H. Viles performed model tests. J. Richards, J. Mayaud and H. Viles wrote and edited the paper. All authors read and approved the final version of the manuscript.

Paper 4 (Chapter 7)

H. Viles, X. Wang and Q. Guo initiated and sought funding for this project. H. Viles conceived the idea for the modelling approach. J. Richards developed the model with advice from J. Mayaud and R. Bailey. J. Richards, J. Mayaud, H. Viles and R. Bailey shaped the experimental design of this study and contributed to the writing and editing of the manuscript. H. Viles, Q. Guo and X. Wang oversaw the project. All authors read and approved the final version of this manuscript.

Appendix B: Earthen heritage value and conservation approach

Published as: Richards, J., Wang, Y., Orr, S., Viles, H., Wang, Y., Orr, S.A. and Viles, H. (2018) Finding Common Ground between United Kingdom Based and Chinese Approaches to Earthen Heritage Conservation. *Sustainability*, 10(9), p.3086. doi: <https://doi.org/10.3390/su10093086>.

Sustainability

MDPI

Article

Finding Common Ground between United Kingdom Based and Chinese Approaches to Earthen Heritage Conservation

Jenny Richards *, Yinghong Wang, Scott A. Orr and Heather Viles

School of Geography and the Environment, University of Oxford, Oxford, OX1 3QY, UK; yinghong.wang@ouce.ox.ac.uk (Y.W.); scott.orr@ouce.ox.ac.uk (S.A.O.); heather.viles@ouce.ox.ac.uk (H.V.)

* Correspondence: jennifer.richards@ouce.ox.ac.uk; Tel.: +44-(0)1865-285070

Received: 25 July 2018; Accepted: 28 August 2018; Published: 30 August 2018

Abstract: Earthen heritage is one of the oldest and universal forms of heritage but its conservation poses many challenges. Establishing international collaborations could provide an efficient, sustainable mechanism to increase knowledge exchange, aiding the development of earthen heritage conservation strategies around the world. However, perceived differences in how Eastern and Western countries value earthen heritage and develop conservation strategies can pose challenges for establishing collaborations. To understand these perceived differences and whether they hinder collaborations, this paper compares British and Chinese heritage conservation policy and practice and then reports the results from an innovative workshop examining the approaches of 13 Chinese and 13 UK based heritage experts and researchers towards earthen heritage conservation. Workshop participants undertook bilingual discussions and completed a co-created questionnaire available in English and Mandarin. Both groups identified historic value as the most important value and maintenance of authenticity and integrity, need for scientific research and site scale conservation as vital considerations for conservation strategies. This study found that to understand the potential for collaboration, individual perspectives need consideration as well as policies and practices. This innovative bilingual, discussion-based approach has potential to aid collaborations for diverse international issues from wildlife conservation to cross-boundary pollution and climate change.

Keywords: earthen heritage; conservation; collaboration; policy; practice; bilingual; discussion; cross-cultural

1. Introduction

Earthen heritage is one of the oldest and universal forms of heritage with sites dating back to Neolithic times [1–3]. Its global importance has been recognized with earthen

heritage comprising 10% of World Heritage Sites [4]. The first international Terra conference took place in 1972 which addressed the protection of earthen heritage and the establishment of national and international networks [2]. Interest in earthen heritage conservation has developed rapidly since the 1990's with research now being undertaken worldwide [5–7]. Nevertheless, earthen heritage conservation still faces many challenges caused by a lack of research into earthen materials [8]; the vulnerability of earthen materials to degradation by environmental processes [4,9]; and the locations of many sites in remote and/or politically fragile areas [4]. The implication of these challenges is seen with earthen heritage sites comprising 33% of the World Heritage in danger list [4].

Earthen heritage conservation and research has been and continues to be strongly directed and influenced by heritage conservation policies and past practice. International heritage conservation policy has developed since the late 1870's through a series of international charters, recommendations, resolutions and declarations [10] as well as through the development of domestic policies and guidelines. Until the 1980's and 1990's, the vast majority of the international documents and heritage conservation practice were based on Western heritage sites and Western approaches to heritage conservation (e.g., Charter of Athens, 1933, The Venice Charter, 1964 and the European Charter of Architectural Heritage, 1975) but applied globally. It was not until the publication of documents such as The Nara Document on Authenticity (1994), that Eastern approaches to heritage conservation were explicitly addressed in built heritage conservation policy. However, Western biases still have the potential to brush over the vast range of heritage conservation practices. When addressing collaborations between Eastern and Western countries, understanding and acknowledging these historic biases is important as notions of an east/west divide can further mask important nuances in conservation practice [11]. Furthermore, as countries subscribe to international policies, countries have autonomy over conservation practices but this means there is a lack of an overarching international heritage conservation policy and so many approaches have been developed for earthen heritage conservation. Previous research has compared heritage conservation policies and past practices to understand the extent of differences, if any, between Eastern and Western countries [10,12–15]. However, despite the worldwide importance of earthen heritage and a great diversity of approaches to its conservation, there have been few studies addressing this specifically for earthen heritage [16].

Earthen heritage conservation research has tended to develop strategies which can be applied to the physical structure of walls and reduce rates of degradation from environmental processes (e.g., wind, precipitation, sediment erosion) or to minimize damage caused by earthquakes. For sites located in low risk areas for earthquakes, strategies to reduce the impact of degradation caused by environmental processes include:

- applying surface treatments such as stabilizers [17,18], additives [19] and consolidants [20–22].
- placing wall caps made of concrete, terracotta and tiling as well as soil and vegetation on top of earthen walls to be used as a sacrificial layer and promote water run off away from the wall [5,23,24].
- adding drainage systems such as surface drains [25], drainage slopes [26,27], drainage pipes [28,29] and damp proof coursing [30] to promote the movement of water away from the site.
- applying structural interventions such as grouting cracks and wooden rod anchorages to the walls [31].

In general, these approaches have initially decreased rates of erosion but over longer time periods, they have tended to have minimal impact [18,21,32] or, in some cases, have increased rates of degradation by causing unintended consequences such as salt mobilization and water pooling [23,33]. The complexity of deteriorative processes impacting earthen heritage suggests that new techniques and approaches need to be researched and trialled to minimize further damage to earthen heritage.

To aid future research into earthen heritage conservation, establishing international collaborations is vital for forming sustainable mechanisms for promoting knowledge sharing and understanding [6,15]. There have previously been several such collaborations [12,34]. However, perceived differences, especially between Western and Eastern countries, in how countries value heritage sites and implement conservation strategies as well as language and geographical barriers, have made collaborations difficult [10,12,35], suggesting that further attempts to elicit common values and approaches towards heritage conservation are required for collaboration to be successful. These perceived differences are seen between the UK and China which have different histories regarding heritage conservation [10]. However, both countries are at the forefront of research on earthen heritage and heritage science more generally, have comprehensive heritage conservation policies and have shown a desire to undertake future collaborative work. This paper focuses on comparing specific countries, rather than wider continental approaches to conservation to allow a deeper discussion and understanding of potential collaboration between researchers.

This study is part of a wider research project involving researchers in the UK and China using computational modelling to assess the suitability of conservation strategies for earthen heritage—focusing on the World Heritage earthen site of Suoyang Ancient City (锁阳城), Gansu Province, northwest China. As such, it is essential to understand why certain conservation strategies are implemented and whether ideas about what constitutes a preferred conservation strategy differ between countries. This study has three goals: (1) to compare heritage conservation policy and practice, past and present, in the UK and China to identify differences and similarities in formal

principles/guidelines and to understand if and how, these differences have played out in heritage conservation. (2) To assess more specifically the potential for future collaborations for earthen heritage conservation, through an investigation of the similarities and differences between small groups of UK based and Chinese experts with backgrounds in conservation practice and conservation and deterioration research. Heritage experts were chosen for this study as in both the UK and China they play a crucial role in developing new strategies and disseminating information to relevant bodies who implement conservation strategies [6,14,35]. Experts from a range of ages and academic positions were included to assess the current potential for collaboration as well as incorporating the views of early career researchers to understand potential future trajectories for collaboration within earthen heritage research. (3) To understand if differences between policy and practice in the UK and China map onto those recorded from the in-depth exploration of UK based and Chinese experts.

2. Materials and Methods

2.1. Comparison of Policies and Practices

National policy documents were chosen for comparison due to the lack of overarching international principles for earthen heritage conservation (Figure 1). Principles for the Conservation of Heritage Sites in China, 2015, (hereafter the China Principles) and Historic England’s Conservation Principles, Policies and Guidance, 2008, (hereafter Historic England’s Conservation Principles) were chosen as both documents are comprehensive and have a national influence over the undertaking of heritage conservation.

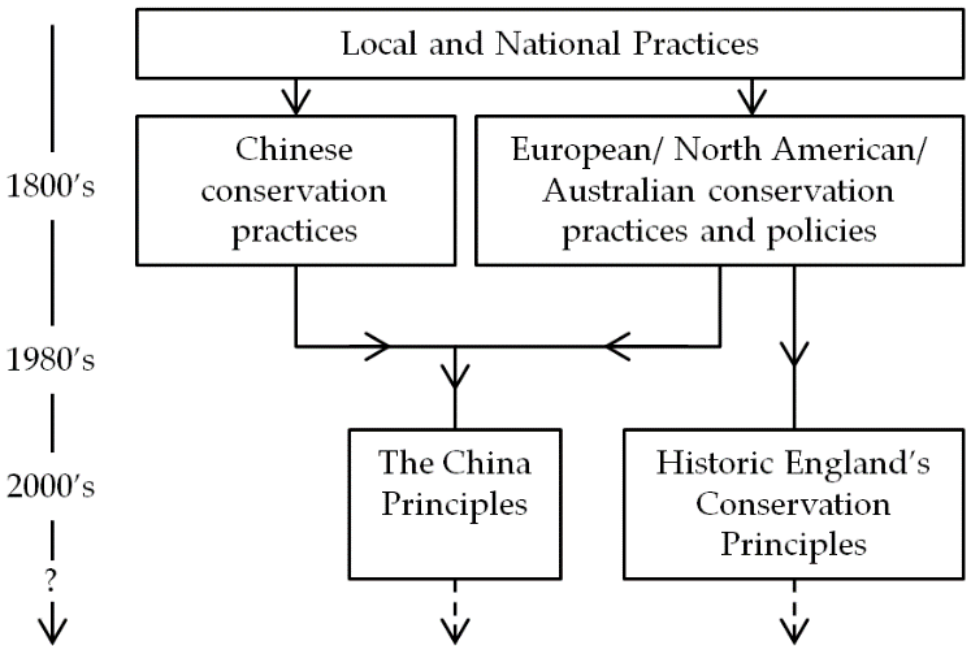


Figure 1. The development of the China Principles and Historic England’s Conservation Principles from regional practices and policies.

In England, Historic England's Conservation Principles provide a framework for conservation practices and managing change in historic environments [36]. In China, Principles for the Conservation of Heritage Sites in China, 2015, (hereafter the China Principles) provide national guidelines for cultural heritage practice [37]. The China Principles were originally produced in 2000 through collaboration between China, Australia and America (Figure 1). It has since been published bilingually with a Mandarin/English glossary of technical terms and concepts to ensure consistent usage of terminology [35] and was revised in 2015. This study uses the 2015 version. Both policies were thematically reviewed and compared.

To compare past heritage conservation practices, a wide literature search including both English and Chinese publications was undertaken for each of the main themes identified in the policies. The search was not limited to earthen heritage to ensure a broad range of heritage practices were assessed and compared.

2.2. Approach to the Workshop

The workshop element of this study was carried out as part of a larger two-day workshop held in March 2018 in the UK. The workshop was attended by 13 Chinese and 13 UK based heritage experts and scientific researchers who undertake work to inform and shape conservation strategies and who have a range of academic and practical experience. The UK based participants were international in profile but as they were working in the UK they are seen as representing current UK approaches to heritage research. All participants had a minimum of a master's degree with over half also having a doctorate and were from a range of career stages from early career, with approximately 25% of participants under 30 years old, to senior researchers.

The workshop was bilingual throughout to recognize the importance of language in communicating technical and nuanced ideas. All resources were available in Mandarin and English and were translated by a researcher who has studied heritage science at a post graduate level in both China and the UK. Additionally, three translators were present to translate introductory presentations, feedback and questions.

At the start of the workshop, all participants were invited to introduce themselves, their work and their background. At the start of every session, the importance of everyone's contribution to the discussions was emphasized. All sessions were held under Chatham House rules to protect participants' anonymity (see www.chathamhouse.org for more information).

The workshop used a mixed method approach to enable the collection of qualitative and quantitative data. Discussions were used to gain a deeper understanding of how participants approached the valuation of earthen heritage sites and its conservation. The discussions also allowed participants the freedom to express and discuss individual views, ask questions and debate contentious topics. A co-created questionnaire

completed anonymously was used to ensure that all participants had the opportunity to express their views and all responses were viewed as equal. It also allowed the collection of quantifiable data.

2.3. Workshop Case Study: Suoyang Ancient City

To focus discussions, Suoyang Ancient City was used as a case study site. Suoyang Ancient City was built in the Han and Tang dynasties along the Silk Road in northwest China, to the north of the Qilian Mountains (Figure 2). It was built largely out of rammed earth as a fortification and communication settlement and also had an extensive irrigation infrastructure. In 2014, it was listed as one of 33 properties that make up the trans-boundary Silk Road World Heritage site.

A Chinese earthen heritage site was chosen as a focus for discussion to move away from the historic Western bias seen in conservation policy and practice. Suoyang was chosen as many of the Chinese researchers and some of the UK based researchers had visited the site. Furthermore, Suoyang is experiencing degradation by wind, sediment and water erosion but lacks a comprehensive long-term conservation plan, thus it provides real conservation challenges that could be discussed throughout the workshop.

An introductory presentation about Suoyang was given to ensure all participants had a baseline knowledge of Suoyang and its conservation challenges. For those who had not visited the site, they were asked to use their knowledge of other earthen heritage sites throughout the workshop.



Figure 2. The site of Suoyang Ancient City showing (a) the inner-city walls (photo credit: Dunhuang Academy) and (b) the Ta'er temple (photo: author's own).

2.3. Discussions

Discussions were held in four groups of 5 to 7 people. Each group had a chairperson and a note taker. Note takers did not attribute any comments to specific participants. The groups were organized such that there were two UK based and two Chinese groups. All

groups had researchers from a range of ages, academic levels and backgrounds and where possible, an equal gender balance. This was chosen after consultation with Chinese and UK based researchers to allow discussion to flow freely within the time available and to ensure participants felt able to present their own views.

There were three discussions which each lasted between 20 to 35 min. The topics for discussion were developed with input from both UK based and Chinese heritage researchers to ensure all participants could contribute. The discussions focused on (1) values associated with Suoyang; (2) factors which need to be considered in designing a conservation strategy; and (3) which aspects of a conservation strategy are the most/least important and which are difficult to implement. At the end of each discussion session, the group chairs fed back to all participants and there was time for questions.

After the third discussion, participants were given six post-it notes, each divided in two with English and Mandarin sections. Participants wrote their three most important and three least important factors for a conservation strategy for earthen heritage and answers were translated. These were brought to the front and arranged into themes.

2.4. Questionnaire

The thematic review of the policy documents and earthen heritage literature was used to create a baseline questionnaire. The questionnaire was designed to gain an insight into (1) how participants value Suoyang and earthen heritage and (2) what participants would view as a preferred conservation strategy. The questionnaire was presented in both Mandarin and English at the workshop for discussion (Figure 3). Participants were asked to critique the questionnaire, assessing if questions were relevant and if all key aspects of earthen heritage conservation were addressed. In addition, this process allowed participants to clarify parts of the questionnaire which may have been open to misinterpretation. Suggestions to alter the baseline questionnaire were made by both Chinese and UK based participants with questions being added, removed and redefined. These suggestions were used to produce a co-created questionnaire available in both Mandarin and English (Figure 3).

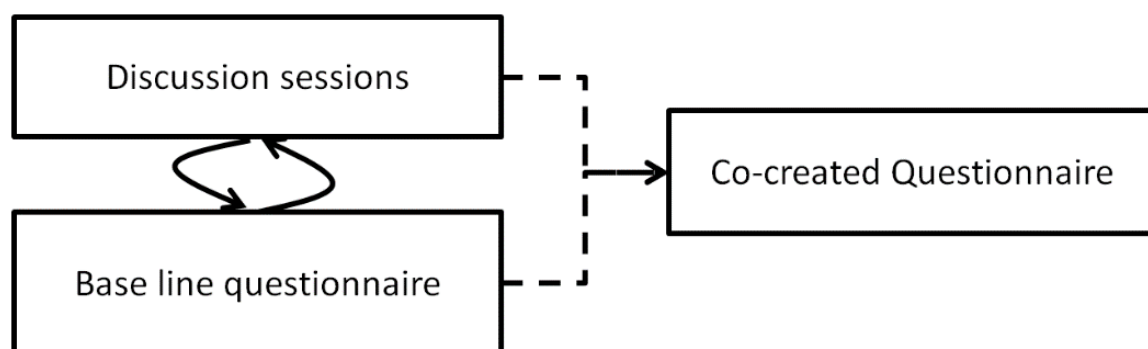


Figure 3. The processes of producing the co-created questionnaire.

The final co-created questionnaire contained six questions on value, 28 questions on what constitutes a preferred conservation strategy and three optional demographic questions (Table 1). Within the final questionnaire were six question types (see Table 1 and Appendix A). The three most common types were:

- A five-point Likert-type scale used for value questions. The scale ranged from 1 (not important) to 5 (very important) with 3 as neutral.
- An adapted seven-point semantic differential/Likert-type scale with true opposites used for questions relating to conservation strategies. Pairs of mutually exclusive words, such as ‘visible’ and ‘not visible,’ were placed at the left and right ends of a horizontal scale. The scale ranged from 3 (left hand side concept is essential) to 0 (neutral) to 3 (right hand side concept is essential).
- An adapted seven-point semantic differential, Likert-type scale with false opposites. This differed from the previous question type as the pairs of words at the opposite ends of the scale were not mutually exclusive. This question type was included to force the respondents to think whether they had a preference towards one option. If both were of equal importance, the participant would choose 0.

With all scales, intermediary numbers did not have word descriptions to produce more equal spacing between numbers. All participants were given as much time as they needed to complete the questionnaire which on average took 15 to 20 min.

Table 1. Questions and possible answers included in the questionnaire.

Question Type	Question Number	Factor Assessing	Possible Answers
Values			
Likert-type scale (1–5)	A	Historic value	1 (Not important)–5 (Very important)
	B	Scientific value	1 (Not important)–5 (Very important)
	C	Artistic value	1 (Not important)–5 (Very important)
	D	Social value	1 (Not important)–5 (Very important)
	E	Cultural value	1 (Not important)–5 (Very important)
	F	Economic value	1 (Not important)–5 (Very important)
Conservation strategy considerations			
Multiple choice (tick one)	1	Application area of strategy	Do nothing; Main body of the wall; Wall foundations; Surrounding environment
	2	Location to reduce degradation	Areas experiencing degradation; Areas at future risk; Areas experiencing <i>and</i> at risk of degradation; All areas of the site
	12	Cheap installation cost	<¥10,000; ¥10,000–100,000; ¥100,000–1,000,000; ¥1,000,000–10,000,000; >¥10,000,000

	13	Cheap annual maintenance cost	<¥1000; ¥1000–10,000; ¥10,000–100,000; ¥100,000–1,000,000; ¥1,000,000–10,000,000; >¥10,000,000
	15b	Minimal people hours for installation	<50 h; 50–200 h; 200–1200 h; 1200–2400 h; >2400 h
	16b	Minimal people hours for monthly maintenance	<1 h; 1–10 h; 10–50 h; 50–100 h; >100 h
Multiple choice (tick all that apply)	6	Application area for strategy	No visible degradation; minor degradation; major degradation
	17	Documentation	No documentation produced; Informal notes/write up; Internal report; External/published report
Semantic differential Likert Type scale. True opposites	3	Visibility	Visible/Not Visible
	4	Material	Human-made/ Natural
	5	Number of parts	One part/Many parts
	7	Scale of strategy	Individual walls/Whole site
	8	Intervention	Interventive/Preventative
	9	Reduce degradation over 10 years	Not at all/Completely
	10	Reduce degradation over 10-50 years	Not at all/Completely
	11	Reduce degradation over 50+ years	Not at all/Completely
	14	Work force	Non-specialized/Highly specialized
	15	People hours for installation	Minimal/Intensive
	16	People hours for maintenance	Minimal/Intensive
	18	Access during strategy installation	Remain open to the public/Be closed to the public
	19	Scientific underpinning	Not researched/Extensively researched
	23	Permanence	Temporary/Permanent
	24	Reversibility	Reversible/Non-reversible
Semantic differential Likert Type scale. False opposites	26	Maintenance of authenticity	Not at all/Completely
	27	Maintenance of integrity	Not at all/Completely
	20	Policy preference	China Principles/Western conservation principles
	21	Knowledge	Scientific knowledge/Local knowledge
	22	Strategy techniques	Innovative/Traditional
	25	Protection	Physical properties/Cultural and social properties

Open	28	Describe your preferred strategy	
Demographic information			
Open	(i)	Nationality	
Multiple choice (tick one)	(ii)	Age	Under 30 years old; 30–45 years old; 45–65 years old; Over 65 years old
	(iii)	Academic qualification	Bachelor’s Degree; Master’s Degree; Doctorate

Analysis of Questionnaire Results

Results from the discussion were reviewed thematically and results from the questionnaire were analysed dependent on question type.

Relative Importance Index (RII) was used to assess the strength of opinions from scalar questions. RII is a non-parametric test which can be used on ordinal data (Appendix B) [38]. The index ranges from 0 to 1 but the meaning of the RII value is dependent on the scale of the question type used (Table 2). For the seven-point semantic differential, Likert-type scales, a high RII value could be caused by either all respondents answering highly on the same side of the scale or by respondents answering highly on different sides of the scale.

Table 2. The meaning of Relative Importance Index (RII) values for three question types.

	Five-Point Likert-Type Scales	Seven-Point Semantic Differential, Likert-Type Scales with True Opposites	Seven-Point Semantic Differential, Likert-Type Scales with False Opposites
$x \rightarrow 0$	Heritage value not important	Ambivalence towards conservation factor	Important to consider factors on both sides of scale
$x = 0.5$	Ambivalence towards heritage value		
$x \rightarrow 1$	Heritage value very important	Factor of conservation strategy is essential	Factor of conservation strategy is essential

To test for the agreement between participant responses, a weighted agreement index was developed by the authors for the seven-point semantic differential, Likert-type scales (Appendix B). The index ranges from –1 to 1 with 1 showing that all participant responses were on the right-hand side of the scale and –1 showing that all respondents responded on the left-hand side of the scale. As the index tends towards 0, there was less agreement among respondents. Neutral responses were not included as they had not shown a preference to either side of the scale.

To compare the difference in responses between Chinese and UK based responses, Mann-Whitney U test was used at a 0.05 level of significance.

3. Results

3.1. Policy and Practice Comparisons

3.1.1. Policy

The China Principles and Historic England's Conservation Principles were found to have many similarities but also some differences in key concepts which could impact on how earthen heritage conservation is undertaken (Table 3). The China Principles regard heritage sites as places with "immovable physical remains created during the history of humankind and that have significance" [37] (p. 58). They also state that the aim of heritage conservation is "to preserve all physical evidence" along with its intangible heritage and to slow future deterioration [37] (p. 61). In contrast, Historic England's Conservation Principles place a much stronger weighting on intangible heritage as they view heritage sites as going beyond the physical to include all characteristics that can contribute to a sense of place [36] (p. 14) and heritage conservation as the process of managing change in ways that will sustain the site's values [36] (Principle 4.2). Current earthen heritage conservation research focuses mainly on protecting physical structures but even though the publication of the China Principles placed a greater emphasis on intangible heritage in Chinese heritage conservation policy [35], the differences between the two sets of principles could cause friction over future considerations of intangible heritage within earthen heritage conservation.

Table 3. Comparison of key concepts in the China Principles (2015) and Historic England's Conservation Principles (2008).

	China Principles	Historic England's Conservation Principles
What is a heritage site?	Immovable physical remains created during the history of humankind and have significance	A site goes beyond the physical material to include all characteristics that contribute to a sense of place
What is the aim of conservation?	To preserve the existing condition and slow deterioration to the site	To manage change to a site that will sustain its values
Values	Historic, artistic, scientific, social and cultural	Historic, evidential, aesthetic and communal
Authenticity	Resides in original materials, workmanship and design	Attributes and elements that most truthfully reflect and embody the heritage values attached to it
Integrity	Preserving the entirety of a site and full range of values	Wholeness and honesty
Conservation techniques	Only techniques proven to be beneficial to reducing degradation at the site should be used. Traditional craftsmanship should be maintained	Traditional materials have known lifetimes and behaviours whereas new materials are much less certain
Reversibility	Conservation treatments should not compromise future treatments	Ability to judge long term impact of changes is limited
Participation	The public have a responsibility and obligation to participate in heritage conservation. All levels of government are responsible for the conservation of sites. Research should be encouraged	Everyone should be able to participate and stakeholders should be encouraged to engage with sites Experts should use knowledge to encourage learning

Both sets of principles emphasize that conservation can only be successful when a site's values are understood. Values are classified in The China Principles as historic, artistic, scientific, social and cultural [37] (p. 61) and in Historic England's Conservation Principles as historic, evidential, aesthetic and communal [36] (pp. 28–32). Despite the different names attributed to value types, there is some overlap between meanings in the two policies (Figure 4). For example, Historic England's communal value derives meaning from people who relate to a site [36] (p. 31) and similarly the China Principles' social and cultural values relate to the benefit that society derives from a site and also the ethnic, regional and religious diversity associated with a site [37] (p. 61). Some values, such as artistic and aesthetic value, do not have an equivalent. In the China Principles, artistic value addresses the artistic creativity and the site's representative style of a particular

period in history and in Historic England's Conservation Principles aesthetic value is derived from how people gain sensory and intellectual stimulation from a site. This suggests some value types can be approximately transferred between countries. However, care is needed to understand and preserve the nuanced differences between value types and furthermore, acknowledge that for some values, earthen sites are judged differently in different countries.

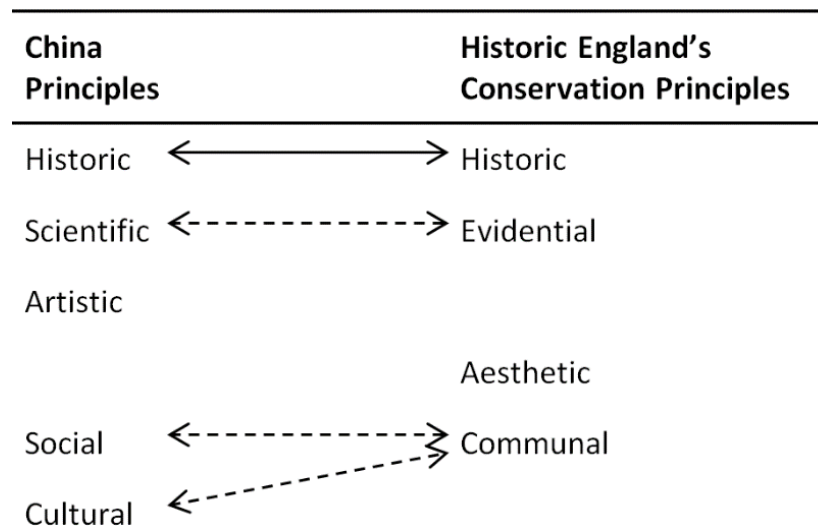


Figure 4. Comparison of values in China Principles (2015) and Historic England's Conservation Principles (2008). The solid arrow represents strong similarities between values. The dashed arrow represents some overlap between values.

Historic England's Conservation Principles view authenticity as a site's attributes and elements that most truthfully reflect and embody the heritage values attached to it [36] (Principle 4.3). Similarly, the China Principles view authenticity as residing in the original materials, workmanship and design along with the continuation of cultural traditions associated with the site [37] (p. 67). In both principles, reconstruction of extant sites is not permitted and any changes to a site should be distinguishable from original material. However, in the China Principles, there is a greater flexibility for reinstatement when the original site has for example partially collapsed, deformed or when reinstatement enables the historic setting to reveal the values of the site [12,39]. This difference in reinstatement could pose problems for earthen heritage conservation research with different standards being viewed as acceptable.

In both principles, integrity focuses on conserving the full range of a site's values within its setting. The China Principles place a heavy emphasis on the use of buffer zones which is also emphasized in UNESCO World Heritage nominations [12].

Both principles emphasize the use of traditional materials and advise against the use of new material until they have been proven effective. However, the China Principles state that conservation measures should not compromise future treatments [37] (p. 68) whereas Historic England's Conservation Principles state that it is difficult to judge the long-term impact of conservation treatments and this should not prevent modest

changes being applied [36] (p. 47). For earthen heritage research, this means that both UK and China have a similar policy approach to the materials and methods to use in conservation strategies but China, adhering to the China Principles, could be more reserved when applying new treatments to sites.

Substantial differences were found over who can participate in the process of conservation. The China Principles are based on a top down approach where the national government holds the ultimate decision making power [6,35], all heritage practitioners are expected to follow them [12] and the public should feel a responsibility and obligation to support heritage conservation [37] (p. 64). In contrast, Historic England's Conservation Principles provide a framework to advise government but they are not dependent on the government's support and there is a greater emphasis on experts engaging and encouraging participation from communities and other stakeholders [36](Principle 2). These differences in governance and participation within heritage conservation have the potential to cause frustrations and tensions within international collaborations while participants become familiar with other countries systems and appreciate their merits—even if they go against personal beliefs about how systems should be organized.

3.1.2. Practice

Despite many similarities between policies, multiple differences between heritage conservation practice in the UK and China have been found, caused in part by historical, cultural, political and practical differences [10,12,40]. According to reviews of conservation in China [6,10,41], contemporary conservation practices which focus on conserving physical remains and historic material of sites were not established until the early 1900s and grew in popularity in the 1980s with the opening up of China. This means conservation practice is still relatively young in China and collaborations need to recognize the challenges caused by this, such as a lack of public awareness.

Cultural differences have also been found to cause differences in heritage conservation practice between the UK and China. For example, in practice, considerations of authenticity in the UK generally reflect Historic England's policy guidelines and are highly related to material concepts with preferences towards minimal intervention. Current understandings of authenticity in the UK developed over the course of the 19th century, with some suggesting that conflicting values surrounding cultural heritage caused the concept of authenticity to rise in importance and go from restoration and conservation being entwined ideas to focusing ideas found in its current definition [42]. In China, authenticity is viewed by some as an imported concept [43] and it is debated whether authenticity should conserve original parts of the site in their present day condition or, if sites should be restored to give the effect of how the site was at its prime as this is argued to give visitors a more authentic experience of visiting the site [44]. The discrepancy has occurred as authenticity is not an indigenous concept in China [43,44]

and so authenticity can either be translated in Mandarin as *yuanzhenxing* (原真性) meaning 'the original true state' or *zhenshixing* (真实性) meaning 'true state'[45]. If *yuanzhenxing* is used, this refers to the original state of the site when it was created thus supporting large scale reconstructions to recreate sites as they were in their heyday. If *zhenshixing* is used, the concept is applied to the current condition of the site. For earthen heritage research this means that those involved need to understand which version of authenticity is being used for the sites and what implications this has for the conservation strategy.

Differences in the governance of and participation in heritage conservation were also found. China's top down structure of governance of heritage conservation means that local voices are not effectively heard, although there has recently been an increased effort to include local groups in conservation strategies [46–48]. In comparison, many UK heritage conservation organizations encourage the inclusion of multiple stakeholders and communities when developing conservation strategies but tensions between expert and local knowledge are still found especially at the planning stage [49,50]. With different stakeholder groups being included in the conservation of different sites, collaborations need to be open about whose voices are heard and how this could affect decisions regarding the conservation of a site.

Finally, it is worth noting that there are also practical challenges for earthen heritage conservation caused by language and geographical barriers. Translating complex technical concepts requires far more than word for word translation as seen with the concept of authenticity [35,45]. It requires someone with a technical understanding of the topic in both languages to be able to translate concepts so they have the same meanings and connotations in both languages even when specific words may not exist in one or other of the languages. In addition, there is the challenge of overcoming the physical distance between collaborators. Internet based communication may be appropriate but in many cases setting up a collaboration as well as undertaking field or site work requires meeting in person. As the distance between China and the UK is vast and travel and visa applications are expensive, this requires enough funding to support such meetings.

3.2. Workshop and Questionnaire Outcomes

3.1.1. Value

Historical value was seen as Suoyang's most important value by both Chinese and UK based respondents with scientific and cultural values also being seen as important (Figure 5). There was general ambivalence towards Suoyang's artistic value. However, in the discussion some UK based participants viewed the site and especially the temple, as beautiful while some actively viewed the sites as lacking artistic value due to its lack of decoration and embellishment.

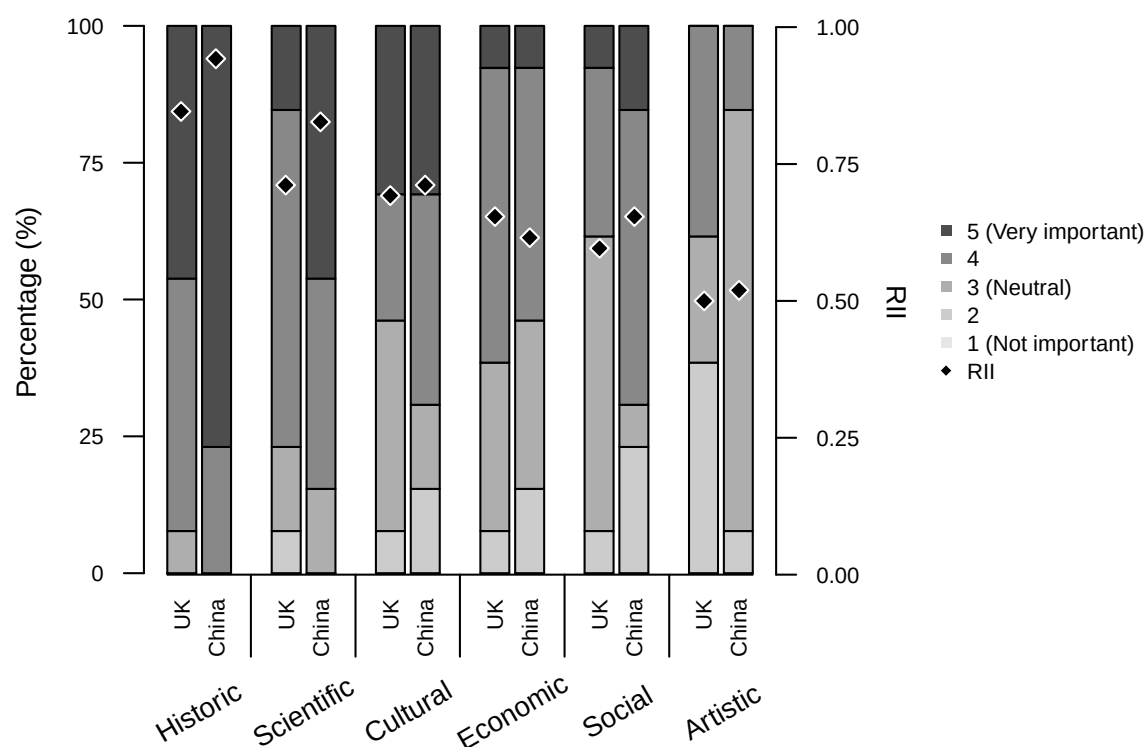


Figure 5. The historic scientific, cultural, economic, social and artistic values associated with Suoyang by UK and Chinese respondents.

In all cases except economic value, the Relative Importance Index (RII) showed that Chinese participants attributed a greater importance to each value (Figure 5). In discussion, Chinese participants shared knowledge that many UK based participants were unaware of, such as a Tang dynasty story where a Chinese General and his army were surrounded at the city by a Western army. When food ran out, they ate a plant called Suoyang to keep them strong and named the city after it.

The importance of economic value was debated. In the post-it note task, economic considerations had the greatest number of post-it notes votes in both the most and least important categories. Participants generally thought, in theory, economic value should not be important but in practice can help fund a site's general upkeep and conservation.

Many participants argued that values could not be viewed in isolation due to links and overlaps between value types. In addition, it was agreed that the value of Suoyang should be viewed within a wider context such as comparing it to the other sites which form the Silk Roads World Heritage site or across wider areas such as China or central Asia. Finally, it was stressed by all groups that understanding a site's value was crucial before any conservation strategy was designed or undertaken.

3.1.2. Conservation Strategies

For both Chinese and UK based respondents, the need for maintaining integrity and authenticity; having scientific research to underpin conservation; and having a site scale

conservation strategy were the conservation attributes with the highest RIs and all showed almost—if not complete—agreement between participants (Figure 6). In addition, most respondents preferred conservation strategies to use both scientific and local knowledge; innovative and traditional techniques; Western and Chinese conservation policies and conserve physical and intangible heritage.

Responses from participants regardless of nationality or background expressed that scientific research should be embedded in conservation strategies and many wanted more scientifically informed site scale, preventative conservation to be used at earthen sites. These strategies were also viewed by participants as beneficial to maintaining Suoyang's authenticity and integrity as strategies would cover the whole site and could modify the environment rather than the site's physical structure. However, participants acknowledged the complexity of applying this in practice as many areas of Suoyang and other earthen sites, require urgent rescue treatments. In these situations, participants argued that treatments may be used without full scientific research and potentially at the detriment of the site's authenticity and integrity.

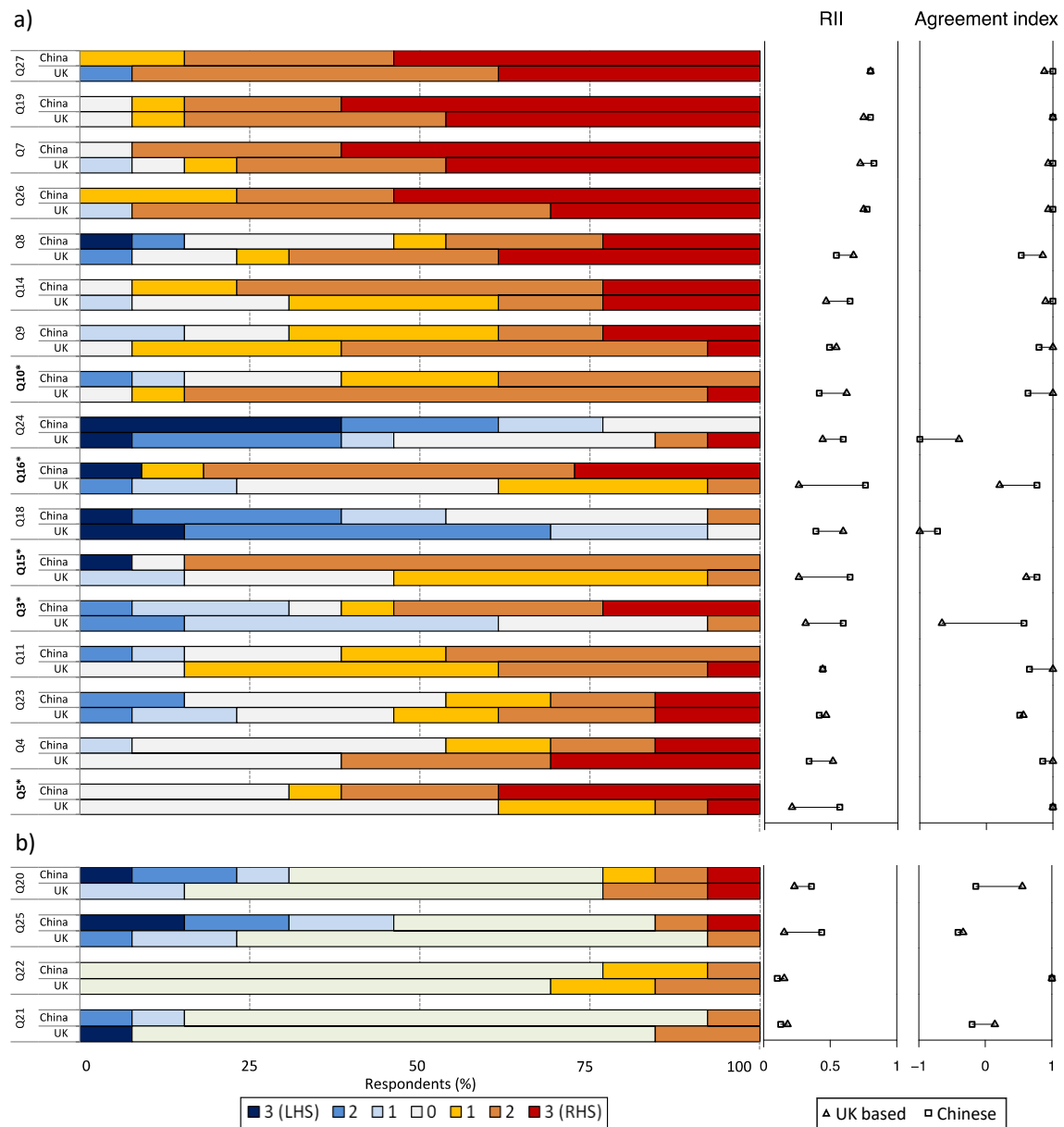


Figure 6. The responses for conservation attributes for Chinese and Western respondents of (a) true opposites and (b) false opposites along with their corresponding RII and Agreement Index values. Refer to Table 2 for Question numbers.

In addition, there was almost complete agreement that short term degradation should be minimized. However, minimizing short term degradation was more essential to UK based respondents than Chinese respondents. In the medium and long terms, there was complete agreement amongst UK based respondents that degradation should be minimized but notably less agreement amongst the Chinese respondents. This difference was significant at the medium term (Table 4, Q10). In discussions, the disjunct between practice and theory was again raised as, in principle, participants supported conservation strategies minimizing long term degradation but recognized the need for rescue conservation which can cause strategies to focus on short term degradation.

Table 4. P values (to 3 decimal places) for questions with significant differences between Chinese and UK based participants. Refer to Table 2 for Question Numbers.

Question Number	<i>p</i> Value
Q3	0.027
Q5	0.041
Q10	0.014
Q15	0.002
Q15b	0.019
Q16	0.002
Q16b	0.001

There were slight preferences shown by Chinese respondents towards using scientific knowledge and the China Principles to inform conservation strategies and by UK based respondents towards using local knowledge and Western conservation principles. The preference held by UK based respondents for using Western principles was notably stronger than the Chinese respondents towards using the China Principles. Chinese respondents showed a stronger preference to conserve physical aspects of heritage sites than UK based respondents. This was similarly seen in the discussion where Chinese respondents reported that the conservation of physical features was a primary goal.

There were significant differences between the UK based and Chinese respondents over the amount of people hours they thought were needed for maintenance and installation (Table 4, Q15–16b). Having intensive people hours for both the maintenance and installation was more essential for Chinese than UK based respondents. Furthermore, when respondents were asked what they would consider as a minimal number of people hours and a cheap cost for installation and maintenance, there was a significant difference between the UK based and Chinese respondents, with Chinese respondents considering more people hours and higher costs to be considered as minimal and cheap than the UK based respondents. Chinese participants highlighted that in theory maintenance would be done daily on site but in practice there are not the resources allocated to make this possible.

In addition, there were also significant differences between the UK based and Chinese respondents over approaches to a conservation strategy's visibility and the number of parts. Chinese respondents would also prefer the strategy not to be visible whereas there was a preference for UK based respondents for the strategy to be visible. The Chinese respondents also showed a stronger preference towards a strategy having more component parts with UK respondents showing little preference.

4. Discussion

4.1. Policy and Practice

Historic England's Conservation Principles and the China Principles provide a broadly similar approach to heritage conservation with regard to what heritage conservation aims to achieve, the importance of understanding the value of a heritage site, valuing authenticity and integrity and preferred conservation strategies. In contrast, there were many differences found between the practices of heritage conservation in the UK and China with differences of what authenticity is and who is able to participate [46–50]. This suggests that, at policy level, there is already the basis for a common language in heritage conservation between UK and China which could be applied directly to earthen heritage research. However, the differences found in practice suggest that further work needs to be undertaken to develop a meaningful common language at a practical level. As all heritage conservation is ultimately practical, for earthen heritage collaborations between the UK and China to be successful, further work is needed to understand why differences between policy and practice emerge and if these processes can be included within a common language to improve cross cultural understandings.

4.2. Values

The set of values in the China Principles were used in the co-created questionnaire to understand how participants valued Suoyang and earthen heritage. All participants at the workshop were used to attaching values to heritage sites but for many of the UK based participants the value types in the questionnaire were new. Furthermore, previous studies suggested that the emphasis in China on the deep cultural meaning and spiritual values of cultural sites which contrasted with the West's emphasis on the functional attributes of heritage sites [15] and the hierarchies of value imposed by Western countries resulted in differences in understanding of the concept of heritage value [44]. Consequently, the similarity between how Chinese and UK based participants valued Suoyang was unexpected but suggests that this transfer in understanding of value types across cultures is likely to have been aided by the overlap of some values in the China Principles' values with those presented by Historic England (Figure 4) and also by this study's approach to sharing knowledge: the co-creation of the questionnaire gave participants the opportunity to discuss and amend definitions of values before answering the questionnaires (Figure 3). This suggests the bilingual discussion-based method enables participants to go beyond an east/west divide by working together to engage critically with concepts from their own country and other countries and to use both in developing more nuanced understandings of the given concepts [11]. This study also demonstrates that locals and non-locals provide different lenses through which to view the importance of Suoyang and other earthen sites; when the understandings from these lenses are combined a fuller understanding of a site's value is achieved. Local knowledge has been argued to be vital in understanding the cultural and social values both in China and the UK [48,51] and was similarly seen with the knowledge held by the Chinese participants in this study with for example the Chinese Army story, which outsiders may not be aware of or have access to the information. Non-locals can provide

a set of understandings on what foreigners might value when visiting. For example, Suoyang was viewed as unusual and beautiful by many UK based participants but ugly and functional for many Chinese based participants. This demonstrates the need to view the site from multiple perspectives as something that is common or boring to one person may be beautiful and rare to someone else. Access to local and non-local knowledge and perspectives requires trust and mutual respect between both parties. This study achieved this between local and non-local heritage experts with accurate translation, explanations of what the knowledge will be used for and valuing opinions equally. Further work is needed to understand the opinions of other stakeholder groups at Suoyang.

It is also interesting to note that economic value is not in the China Principles or Historic England's Conservation Principles, despite both principles emphasizing site sustainability and role within the tourism industry. At this workshop, the tension between the ideal that economic value should not be viewed as important versus the reality that the economic value of a site helps fund conservation was expressed by both UK based and Chinese participants. In addition to common approaches, these common challenges could also be used as a basis for forming collaborations.

These findings show that heritage experts from countries with different histories regarding heritage conservation, which have different heritage conservation policies and past practices, can effectively come to a mutual understanding of a site's value, by discussing and debating issues and new concepts in a bilingual environment. It also shows how collaborations have the potential to enrich the value of earthen heritage sites with different groups identifying their own specific areas of value.

4.3. Conservation Strategies

This study found that Chinese and UK based heritage experts generally agreed that concepts and issues such as authenticity, integrity, scientific underpinning and conserving physical and intangible values of a site were the most important to consider when devising a conservation strategy for Suoyang. This is seemingly unsurprising as both English and Chinese policies stress the importance of these concepts and studies have found that in practice there is a similar emphasis on their consideration [6,45,52]. However, this study found that it is notable that there were compromises made by participants in how they would theoretically undertake conservation and what they are willing to accept in practice. For example, participants from both countries in theory would maintain authenticity by conserving present day materials, being minimally invasive and altering the environmental conditions. However, in practice, participants accepted that for some conservation such as rescue conservations, strategies may need to be applied to the physical structure of the wall. Similarly, for scientific underpinning, researchers theoretically wanted conservation strategies to be fully researched. However, in practice, due to a lack of historical data for earthen heritage, the large

number of earthen sites in need of conservation and a lack of financial investment into earthen heritage, participants acknowledged that conservation strategies may not be fully researched. This suggests that for earthen heritage collaboration to be successful, all parties need to understand what each party considers as an ideal solution but also what they would be willing to compromise on to implement a strategy in practice. The similarities between the UK based and Chinese participants' approaches to earthen heritage conservation both in theory and practice suggest that there is common ground between these parties even when compromises have been taken into consideration.

The majority of Chinese and UK based heritage experts also agreed that having a site scale conservation strategy applied to areas of the site experiencing degradation and at risk of future degradation was important. Historic England's Conservation Principles does not provide guidance on spatial scales at which conservation should be undertaken but states that conservation strategies are only harmful if the significance of a site is eroded [36] (p. 43). In contrast, the China Principles states that intervention should be on areas of heritage at risk of degradation or areas most at need [37] (p. 68). This difference in findings between the Chinese participants and the China Principles indicates the presence of a Chinese Policy/Participant disagreement (see Figure 7). This could be because the China Principles are generalized for all immovable heritage sites and so does not specifically consider the vulnerability of earthen heritage to degradation. Furthermore, the practicalities of applying conservation strategies at a site scale should be considered within a collaboration. The complexity of site scale conservation mean that collaborations are likely to be needed for longer periods of time and also increases the number of potential misunderstandings between collaborators. However, the findings from this study have shown that complex problems can be effectively tackled with clear communication and equal treatment amongst members.

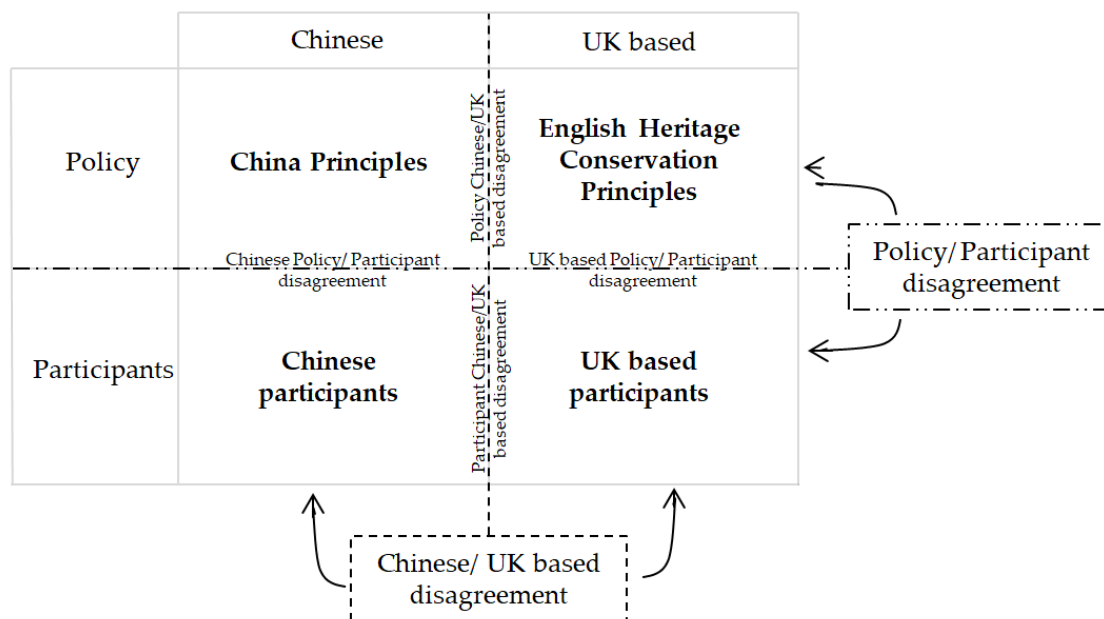


Figure 7. A diagrammatic representation of two types of disagreement that can occur when trying to find common ground for earthen heritage conservation between China and the UK: (i) Policy/Participant disagreement and (ii) Chinese/UK based disagreement. Where disagreements only applied to one row or column, they are referred to by the titles on the inside of the diagram for example, Chinese Policy/Participant disagreement.

This study also found that there are further challenges for collaboration as there are significant differences between UK based and Chinese respondents with issues such as minimizing degradation and the practicalities for implementing conservation strategies, even though the China Principles and Historic England's Conservation Principles are broadly similar. This difference between the UK based and Chinese participants indicates that for these issues there is a Participant Chinese/UK based disagreement (Figure 7). This could have occurred as many of the Chinese participants had implemented conservation strategies, including rescue conservation, on site but the UK based participants had limited on site experience. Therefore, the Chinese participants are likely to be more aware than their UK counterparts of the complexities and thus the resources needed for implementing a conservation strategy on site and the limitations of conservation strategies at reducing degradation. In addition, it is interesting that the importance of degradation over the three timescales remains relatively stable for the Chinese respondents but for the Western respondents there is a significantly lower importance placed on minimizing long term degradation. This could be a reflection of Historic England's Conservation Principles statement that the ability to judge the long-term impact of a strategy is limited on the UK based participants. These differences show that similarities in policies do not always translate into similar practices between heritage experts. This highlights the importance of being aware of participants' backgrounds and previous experience to understand how participant's previous experiences may feed into their future conservation practices.

Finally, this study found that there were also differences between the responses from UK based and Chinese respondents which reflect differences in policy and past practice. The stronger preference for Chinese respondents to preserve the physical structure of a wall could reflect the China Principles placing a larger emphasis on conserving tangible rather than intangible heritage compared to Historic England's Conservation Principles. Similarly, the difference in Chinese and UK based respondents towards the visibility of a conservation strategy could be caused by differing ideas of integrity and authenticity [43,44]. The UK based respondents' preference towards a visible strategy could be influenced by Historic England's Conservation Principles definition of integrity which is based around the idea of honesty and for conservation treatments to be able to be differentiated from the historic material. If visitors to a site are also able to differentiate between the treatment and historic material, the treatment needs to be visible. In the China Principles, conservation treatments are also supposed to be distinguishable from historic material (p. 45). However, as seen in practice with the different translations of authenticity, it is also common for sites to be restored back to an original state with limited emphasis placed on the differentiation between historic and new materials [45]. This suggests that in these cases both Policy/Participant and Chinese/UK based disagreements are present (Figure 7) and could pose the greatest challenge for finding common ground for earthen heritage conservation.

This study shows that even if countries' policies and practices have previously been similar, for collaboration it cannot be assumed that participants will follow their policy guidelines or past practices. Instead, the process for finding common ground for collaborations is specific to individual groups of people and individual earthen heritage sites. This study shows that establishing a bilingual environment where all participants are able to present their views can provide a pathway for discussion, debate and ultimately the potential for promoting and increasing the success of collaborations both for earthen heritage conservation and potentially many other areas of research.

5. Conclusions

This study compared heritage conservation policy, practice and heritage experts' opinions to assess the extent to which there is common ground between UK based and Chinese approaches to earthen heritage conservation. A bilingual workshop with discussion sessions and a co-created questionnaire were used to understand how Chinese and UK based heritage experts value earthen heritage sites and what they view as important properties for a conservation strategy. Suoyang Ancient City, China, was used as a case study to focus discussions during the workshop.

This study found that for both UK based and Chinese heritage experts, historic value was the most important and artistic value the least important value for the earthen heritage site of Suoyang. It also found that concepts and issues of integrity, authenticity, scientific underpinning, the scale of the conservation strategy, conserving physical and intangible

values of a site and methods used to undertake conservation were viewed as very important by both sets of experts. However, there were also some significant differences between the Chinese and UK based heritage experts, such as their approaches to installing and maintaining conservation strategies.

Overall, the similarities and differences in participant responses, policies and practice show the importance of acknowledging the wide array of approaches towards earthen heritage conservation. This study showed that to understand if two (or more) groups will be able to undertake successful collaboration, it is not enough to compare policies and past practices but that also the opinions of the specific people involved need to be considered. To enable these opinions to be honestly and openly expressed, this study has shown that a bilingual, workshop approach enabled respectful discussion and debate. The similarities between UK based and Chinese experts found in this study suggest similar groups of heritage experts could also use this process to find common ground which could be used as a basis for future collaborations. Undertaking a field based meeting could be a potential next step to further strengthen collaborations.

Author Contributions: Conceptualization, J.R. and H.V.; Data curation, J.R. and S.A.O.; Formal analysis, J.R.; Funding acquisition, H.V.; Investigation, J.R. and Y.W.; Methodology, J.R., Y.W. and H.V.; Project administration, H.V.; Resources, J.R. and Y.W.; Supervision, H.V.; Validation, J.R., Y.W., S.A.O. and H.V.; Visualization, J.R. and S.A.O.; Writing—original draft, J.R.; Writing—review & editing, Y.W., S.A.O. and H.V.

Funding: This research was funded by UK Engineering and Physical Sciences Research Council (EPSRC) grant for the Centre for Doctoral Training Science and Engineering in Art, Heritage and Archaeology (EP/L016036/1) in association with the Getty Conservation Institute. The workshop was made possible by funding from the EPSRC Global Challenge Research Fund Institutional Sponsorship 2017.

Acknowledgments: We are grateful to all the participants in this study for sharing their knowledge and experience with us throughout this study. We are also grateful to Hong Zhang, Faguo He and Linyi Zhao for their assistance with translation and advice which allowed the workshop to run smoothly. We thank the two anonymous reviewers for their helpful feedback on this paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Six question types were used in the questionnaire to address a range of questions.

1. Single choice tick box questions were used to understand the preferred choice of a respondent or to quantify/calibrate a concept.
2. Multiple choice tick box questions were used to understand the range of actions a respondent might choose.

3. A five-point Likert-type scale was used for the questions relating to value. The scale ranged from 1 (not important) to 5 (very important) with 3 as neutral. Intermediary numbers did not have word descriptions to produce more equal spacing between the numbers on the scale.
4. An adapted seven-point semantic differential/Likert-type scale with true opposites was used for questions relating to conservation strategies. Pairs of mutually exclusive words, such as “visible” and “not visible,” were placed at the left and right ends of a horizontal scale. The scale ranged from 3 (left hand side concept is essential) to 0 (neutral) to 3 (right hand side concept is essential). As with the five point Likert-type scale, the intermediary numbers did not have word descriptions attached to them to produce more equal spacing between the numbers on the scale.
5. An adapted seven-point semantic differential, Likert-type scale with false opposites was also used for questions relating to conservation strategies. This differed from the previous question type as the pairs of words at the opposite ends of the scale were not mutually exclusive. These questions were included to force the respondents to think about which they cared about more. If both were of equal importance, they would choose “0.”
6. Open questions were used to asking the respondents to describe their preferred conservation strategy. This allowed space for any comments not raised previously in the discussion to be expanded upon.

Appendix B

Calculation of RII and Agreement Index.

The Relative Importance Index (*RII*) was used to assess the strength of response participants attributed to a given question. It is calculated by:

$$RII = \frac{\sum w}{(A - Z) \times N} = \frac{0n_1 + n_2 + 2n_3 + 3n_4 + 4n_5}{4N}$$

where *w* is the weighting, *A* is the highest score a respondent could give, *Z* is the lowest score a respondent could give and *N* is the total number of respondents. The highest score, *A*, needs to be offset by the lowest score, *Z*, so the scale for the scores starts at 0. The equation above also gives an example of how the weighting (*w*) is calculated for the 5 point Likert-type questions where, *n*₁ is the number of respondents for “1,” *n*₂ is the number of respondents for “2,” *n*₃ is the number of respondents for “3,” *n*₄ is the number of respondents for “4” and *n*₅ is the number of respondents for “5.”

The Agreement Index was developed by the authors to calculate the agreement between respondents. The index was calculated by:

$$\text{Agreement Index} = 2 \left(\frac{n_{1RHS} + 2n_{2RHS} \dots + in_{iRHS}}{in_{iLHS} \dots + 2n_{2LHS} + n_{1LHS} + n_{1RHS} + 2n_{2RHS} \dots + in_{iRHS}} \right) - 1$$

where n_{1RHS} is the number of respondents for “1” on the right hand side of the scale, n_{2RHS} is the number of respondents for “2” on the right hand side of the scale, n_{iRHS} is the number of respondents for the highest score on the right hand side of the scale, n_{iLHS} is the number of respondents for the highest score on the left hand side of the scale, n_{2LHS} is the number of respondents for “2” on the left hand side of the scale and n_{1LHS} is the number of respondents for “1” on the left hand side of the scale. Neutral responses were not included as they had not shown a preference to either side of the scale.

References

1. Houben, H.; Balderrama, A.A.; Simon, S. Our earthen architectural heritage: Materials research and conservation. *MRS Bull.* 2004, 25, 338–341, doi:10.1557/mrs2004.101.
2. Balderrama, A.A. The conservation of earthen architecture. *Conserv. Getty Conserv. Inst. Newsl.* 2001, 16, 4–11.
3. Twiss, K.C. The Neolithic of the Southern Levant. *Evol. Anthropol.* 2007, 16, 24–35, doi:10.1002/evan.20113.
4. The World Heritage Programme on Earthen Architecture. World Heritage: Inventory of Earthen Architecture, 2012. Available online: (accessed on 22 November 2017).
5. Correia, M.; Guerrero, L.; Crosby, A. Technical strategies for conservation of Earthen archaeological architecture. *Conserv. Manag. Archaeol. Sites* 2015, 17, 224–256, doi:10.1080/13505033.2015.1129799.
6. Zhu, Z.; Eckfeld, T. The development of conservation practices in China from the 1980s to the present. *AICCM Bull.* 2016, 37, 26–34, doi:10.1080/10344233.2016.1206287.
7. Matero, F.; Cancino, C. The conservation of earthen archaeological heritage: An assessment of recent trends. In *TERRA 2000: 8th International Conference on the Study and Conservation of Earthen Architecture*, Torquay, Devon, UK, May 2000; James & James: London, UK, 2000; pp. 11–21.
8. Correia, M. *Conservation in Earthen Heritage: Assessment and Significance of Failure, Criteria, Conservation Theory, and Strategies*; Cambridge Scholars Publishing: Cambridge, UK, 2016; ISBN 9781443889292.
9. Shao, M.; Li, L.; Wang, S.; Wang, E.; Li, Z. Deterioration mechanisms of building materials of Jiaohe ruins in China. *J. Cult. Herit.* 2013, 14, 38–44, doi:10.1016/j.culher.2012.03.006.
10. Jun, Z. Comparison of Heritage Conservation Philosophies in China and Other Countries. In *International Principles and Local Practices of Cultural Heritage Conservation*; ICOMOS China, Ed.; ICOMOS China: Beijing, China, 2014; pp. 40–61.

11. Winter, T. Beyond Eurocentrism? Heritage conservation and the politics of difference. *Int. J. Herit. Stud.* 2014, 20, 123–137, doi:10.1080/13527258.2012.736403.
12. Qian, F. China's Burra Charter: The Formation and Implementation of the China Principles. *Int. J. Herit. Stud.* 2007, 13, 255–264, doi:10.1080/13527250701228213.
13. Forster, A.M.; Thomson, D.S.; Richards, K.; Pilcher, N.; Vettese, S. Western and Eastern building conservation philosophies: Perspectives on permanence and impermanence. *Int. J. Archit. Herit.* 2018, in press.
14. Zhan, G. Viewing the China Principles in the International Context. In *International Principles and Local Practices of Cultural Heritage Conservation*; ICOMOS China, Ed.; ICOMOS China: Beijing, China, 2014; pp. 31–39.
15. Zhu, Y. Some thoughts on comparison of heritage conservation in historic cities in China and the West: A transcultural perspective. *Southeast Cult.* 2011, 221, 118–122.
16. Bin, J. Influence of the China Principles on Archeological Site Conservation in China. In *International Principles and Local Practices of Cultural Heritage Conservation*; ICOMOS China, Ed.; ICOMOS China: Beijing, China, 2014; pp. 183–193.
17. Elert, K.; Sebastián, E.; Valverde, I.; Rodriguez-Navarro, C. Alkaline treatment of clay minerals from the Alhambra Formation: Implications for the conservation of earthen architecture. *Appl. Clay Sci.* 2008, 39, 122–132, doi:10.1016/j.clay.2007.05.003.
18. Elert, K.; Pardo, E.S.; Rodriguez-Navarro, C. Alkaline activation as an alternative method for the consolidation of earthen architecture. *J. Cult. Herit.* 2015, 16, 461–469, doi:10.1016/j.culher.2014.09.012.
19. Zhang, H.-Y.; Zhu, S.-B.; Li, M.; Zhang, X.-C. Water Repellency of Monument Soil Treated by Tung Oil. *Geotech. Geol. Eng.* 2016, 34, 205–216, doi:10.1007/s10706-015-9939-8.
20. Selwitz, C.; Coffman, R.; Agnew, N. The getty adobe research project at Fort Selden III: An evaluation of the application of chemical consolidants to test walls. In *6th International Conference on the Conservation of Earthen Architecture*; Agnew, N., Ed.; The Getty Institute: Los Angeles, CA, USA, 1990; pp. 255–260.
21. Selwitz, C. Saving the Fort Selden ruins: The use of a composite blend of chemicals to stabilize fragile historic adobe. *Conserv. Manag. Archaeol. Sites* 1995, 1, 109–116, doi:10.1179/135050395793137108.
22. Li, Z. Consolidation of a Neolithic earthen site with potassium silicate. In *6th International Conference on the Conservation of Earthen Architecture: Adobe 90 preprints*; Grimstad, K., Ed.; Getty Conservation Institute: Los Angeles, CA, USA, 1990; pp. 295–301.

23. Oliver, A. Conservation of earthen archaeological sites. In *Terra Literature Review: An Overview of Research in Earthen Architecture Conservation*; Avrami, E.C., Guillaud, H., Hardy, M., Eds.; The Getty Institute: Los Angeles, CA, USA, 2008; pp. 80–96.
24. Alva, A.; Chiari, G. Protection and conservation of excavated structures of mudbrick. In *Conservation on Archaeological Excavations, with Particular Reference to the Mediterranean Area*. Centre for the Study of the Preservation and Restoration of Cultural Property; Stanley-Price, N., Ed.; ICCROM: Rome, Italy, 1995; pp. 101–112.
25. Chaudhry, C.; Sikka, S. Conservation treatments for earthen structures in the Western Himalayas of India. *APT Bull.* 2009, 40, 35–42, doi:10-2307/40284489.
26. Oliver, A.; Getty Adobe Project; Getty Conservation Institute; Museum of New Mexico. Fort Selden Adobe Test Wall Project: Phase I: Final Report; Getty Conservation Institute: Los Angeles, CA, USA, 2000.
27. Caperton, T. Fort Selden Ruins Conservation. In *6th International Conference on the Conservation of Earthen Architecture: Adobe 90 preprints*; Grimstad, K., Ed.; Getty Conservation Institute: Los Angeles, CA, USA, 1990; pp. 209–211.
28. Fodde, E.; Khan, M.S. Affordable Monsoon Rain Mitigation Measures in the World Heritage Site of Moenjodaro, Pakistan. *Int. J. Archit. Herit.* 2013, 1–22, doi:10.1080/15583058.2013.771293.
29. Lister, R.H.; Lister, F.C. Aztec Ruins on the Animas, Excavated, Preserved and Interpreted; Western National Parks Association: Tuscon, AZ, USA, 1987.
30. Hughes, R. A review of works at the world heritage monument of moenjodaro, Pakistan. In *Preserving Archaeological Remains In Situ*; Corfield, M., Hinton, P., Nixon, T., Pollard, M., Eds.; Museum of London Archaeology Service: London, UK, 1998; pp. 26–30.
31. Li, Z.; Wang, X.; Sun, M.; Chen, W.; Guo, Q.; Zhang, H. Conservation of Jiaohe ancient earthen site in China. *J. Rock Mech. Geotech. Eng.* 2011, 3, 270–281, doi:10.3724/SP.J.1235.2011.00270.
32. Chiari, G. Chemical surface treatments and capping techniques of earthen structures: A long-term evaluation. In *6th International Conference on the Conservation of Earthen Architecture: Adobe 90 preprints*; Grimstad, K., Ed.; The Getty Institute: Los Angeles, CA, USA, 1990; pp. 267–273.
33. Warren, J. *Conservation of Earth Structures*; Butterworth-Heinemann: Oxford, UK, 1999.
34. Arzaga, A.G.; Baca, L.F.G.; Contreras, F.U. International Collaborations to Preserves Earthen Architectural Heritage. In *Terra 2008: The 10th International Conference on the Study and Conservation of Earthen Architecture*; Rainer, L., Rivera, A.B., Gandreau, D., Eds.; The Getty Conservation Institute: Los Angeles, CA, USA, 2008; pp. 383–387.

35. Agnew, N.; Demas, M.; Sullivan, S. The development of the China Principles: A Review to Date. In *International Principles and Local Practice of Cultural Heritage Conservation*; ICOMOS China, Ed.; ICOMOS China: Beijing, China, 2014; pp. 11–30.
36. Drury, P.; McPherson, A. *Conservation Principles Policies and Guidance for the Sustainable Management of the Historic Environment* 2008; English Heritage: London, UK, 2008.
37. ICOMOS China. *Zhongguo Wen Wu Gu Ji Bao Hu Zhun Ze = Principles for the Conservation of Heritage Sites in China*, Rev. ed.; Wen wu chu ban she: Beijing, China, 2015.
38. Sodangi, M.; Khamdi, M.F.; Idrus, A.; Hammad, D.B.; AhmedUmar, A. Best Practice Criteria for Sustainable Maintenance Management of Heritage Buildings in Malaysia. *Procedia Eng.* 2014, 77, 11–19, doi:10.1016/J.PROENG.2014.07.017.
39. Zhu, G. China's architectural heritage conservation movement. *Front. Archit. Res.* 2012, 1, 10–22, doi:10.1016/J.FOAR.2012.02.009.
40. Winter, T. Heritage conservation futures in an age of shifting global power. *J. Soc. Archaeol.* 2014, 14, 319–339, doi:10.1177/1469605314532749.
41. Zhou, L. Thirty Years of Chinese Cultural Heritage Protection. *Conserv. Archit. Herit.* 2008, 12, 1–5.
42. Starn, R. Authenticity and historic preservation: Towards an authentic history. *Hist. Hum. Sci.* 2002, 15, 1–16, doi:10.1177/0952695102015001070.
43. Xu, H.; Wan, X.; Fan, X. Rethinking authenticity in the implementation of China's heritage conservation: The case of Hongcun Village. *Tour. Geogr.* 2014, 16, 799–811, doi:10.1080/14616688.2014.963662.
44. Zhu, Y. Cultural effects of authenticity: Contested heritage practices in China. *Int. J. Herit. Stud.* 2015, 21, 594–608, doi:10.1080/13527258.2014.991935.
45. Lu, Z. Evolution of Cultural Heritage Conservation Philosophy Through the Lens of Revised China Principles. In *International Principles and Local Practices of Cultural Heritage Conservation*; ICOMOS China, Ed.; ICOMOS China: Beijing, China, 2014; pp. 1–10.
46. Han, F.; Yang, Z.; Shi, H.; Liu, Q.; Wall, G. How to Promote Sustainable Relationships between Heritage Conservation and Community, Based on a Survey. *Sustainability* 2016, 8, 886–896, doi:10.3390/su8090886.
47. Fan, L. International influence and local response: Understanding community involvement in urban heritage conservation in China. *Int. J. Herit. Stud.* 2014, 20, 651–662, doi:10.1080/13527258.2013.834837.
48. Lui, T. China's Current State and Future Challenges for the Practice of Public Participation in Cultural Heritage Conservation. In *International Principles and Local Practices of Cultural Heritage Conservation*; ICOMOS China, Ed.; ICOMOS China: Beijing, China, 2014; pp. 225–241.

49. Pendlebury, J.; Townshend, T. The Conservation of Historic Areas and Public Participation. *J. Archit. Conserv.* 2014, 5, 72–87, doi:10.1080/13556207.1999.10785244.
50. Townshend, T.; Pendlebury, J. Public participation in the conservation of historic areas: Case-studies from north-east England. *J. Urban Des.* 1999, 4, 313–331, doi:10.1080/13574809908724453.
51. Jokilehto, J. Engaging conversation: Communities, place and capacity building. In *Heritage, Conservation and Community: Engagement, Participation and Capacity Building*; Chitty, G., Ed.; Routledge, Taylor & Francis Group: New York, NY, USA; London, UK, 2017; pp. 17–34.
52. Wang, X. Conservation and management practices of the Mogao grottoes based on the principles for the conservation of heritage sites. In *International Principles and Local Practices of Cultural Heritage Conservation*; ICOMOS China, Ed.; ICOMOS China: Beijing, China, 2014; pp. 154–165.

© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>)

Appendix C: Supporting Information for Paper 3 (Chapter 6)

Introduction

This Supporting Information provides additional material to support the development of the Vegetation and Sediment TrAnsport model for Heritage Deterioration (ViSTA-HD). It presents the data used to inform parameterizations in ViSTA-HD as well as additional verification tests for both the environmental and deterioration modules.

C.1. Field data used in parameterizing ViSTA-HD

Environmental data collected at Suoyang Ancient City were used to parameterize processes in ViSTA-HD's environmental and deterioration modules. Where relevant, data collected at Suoyang were combined with the datasets originally used to build ViSTA (Mayaud et al., 2017a).

C.1.1 Parameterizing the environmental module

C.1.1.1 Seasonality of climate at Suoyang

Wind velocity was recorded at Suoyang between September 2015 and August 2016 using an automatic weather station (Figure C.1). The climate at Suoyang has strong seasonal patterns with strong easterly winds dominating in summer and weak westerlies and south-easterlies dominating in winter. This strong seasonality was used to justify setting the temporal scale of each iteration to 3 months.

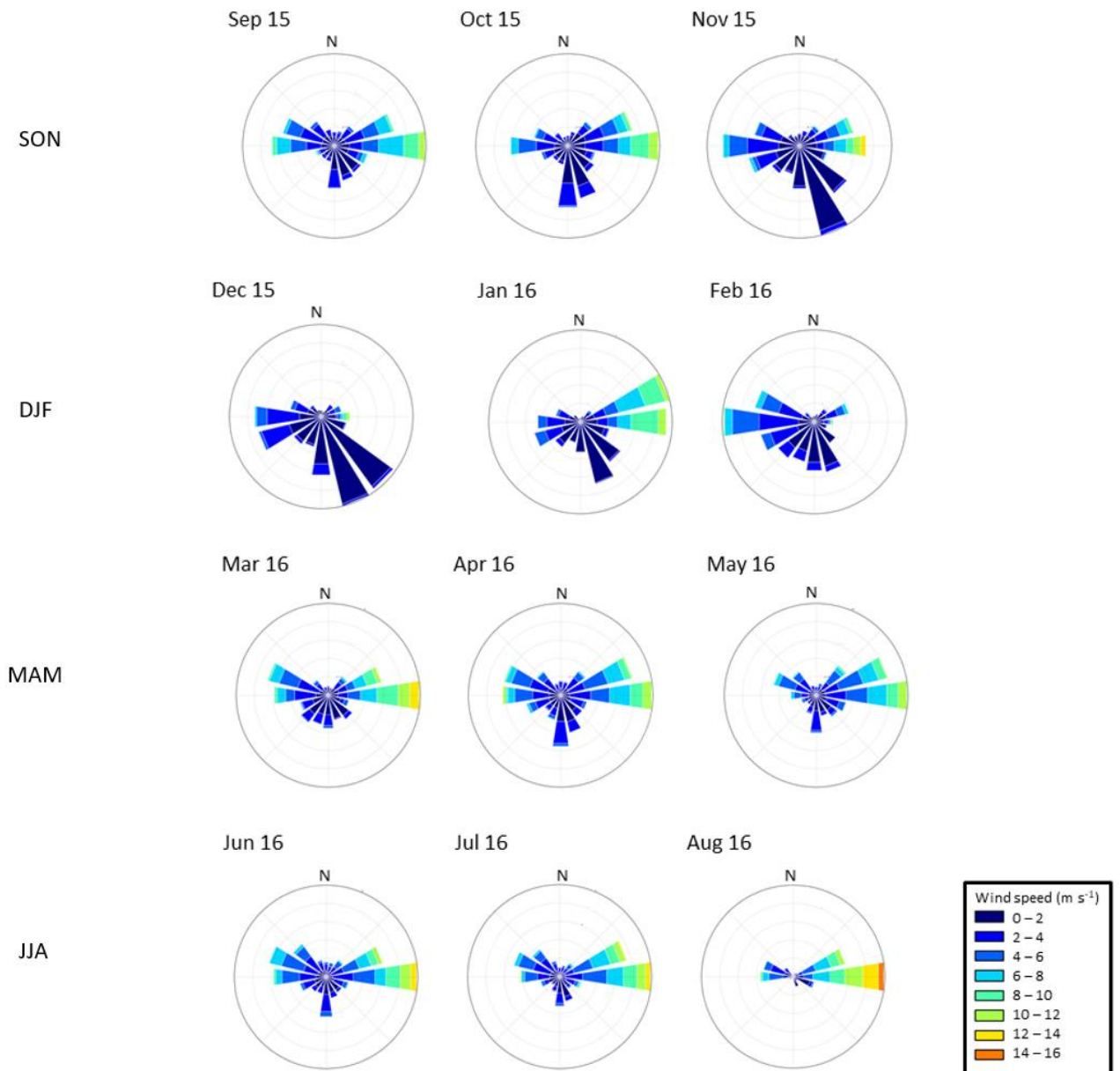


Figure C.1: Wind velocity recorded at Suoyang between September 2015 and August 2016, grouped into four seasons.

C.1.1.2 Wind velocity recovery

In Mayaud et al.'s (2017a) validation of wind recovery in the lee of vegetation elements in the Kalahari, they did not use data from elements with a porosity less than 30%.

Preliminary optical porosity tests undertaken at Suoyang. Results showed that whilst the dominant vegetation species had similar structural features to those used to parameterize ViSTA, the range of porosities at Suoyang was significantly greater than in

the Kalahari, with some plants having optical porosities as low as 2%. To capture a fuller range of wind recovery distances, wind velocity data from around low-porosity elements in Suoyang were combined with Mayaud et al.'s (2017a) original dataset. This combined dataset was used to parameterize wind flow in ViSTA-HD.

Using the methodology described in the open-source methodology of Mayaud et al. (2017a), we used the combined Kalahari-Suoyang dataset to determine the parameterisation of the mean normalized wind velocity (u_0) at 1 h downwind of the vegetation element (where h is the height of the plant) as:

$$u_0 = 0.0002p^2 - 0.0117p + 0.3345$$

(Equation C.14)

And the rate of wind recovery in the lee of the vegetation, determined by the b coefficient, as:

$$b = \begin{cases} 0.32 & (p < 65\%) \\ 0.65 & (p \geq 65\%) \end{cases}$$

(Equation C.15)

where p is the porosity of the vegetation element (Figure C.2).

Bayesian selection criteria is a criterion for selecting between a finite set of models that determines the optimum number of parameters within the model, without overfitting. We applied this criterion to our wind recovery data in Microsoft Excel to select the wind recovery model used in ViSTA-HD.

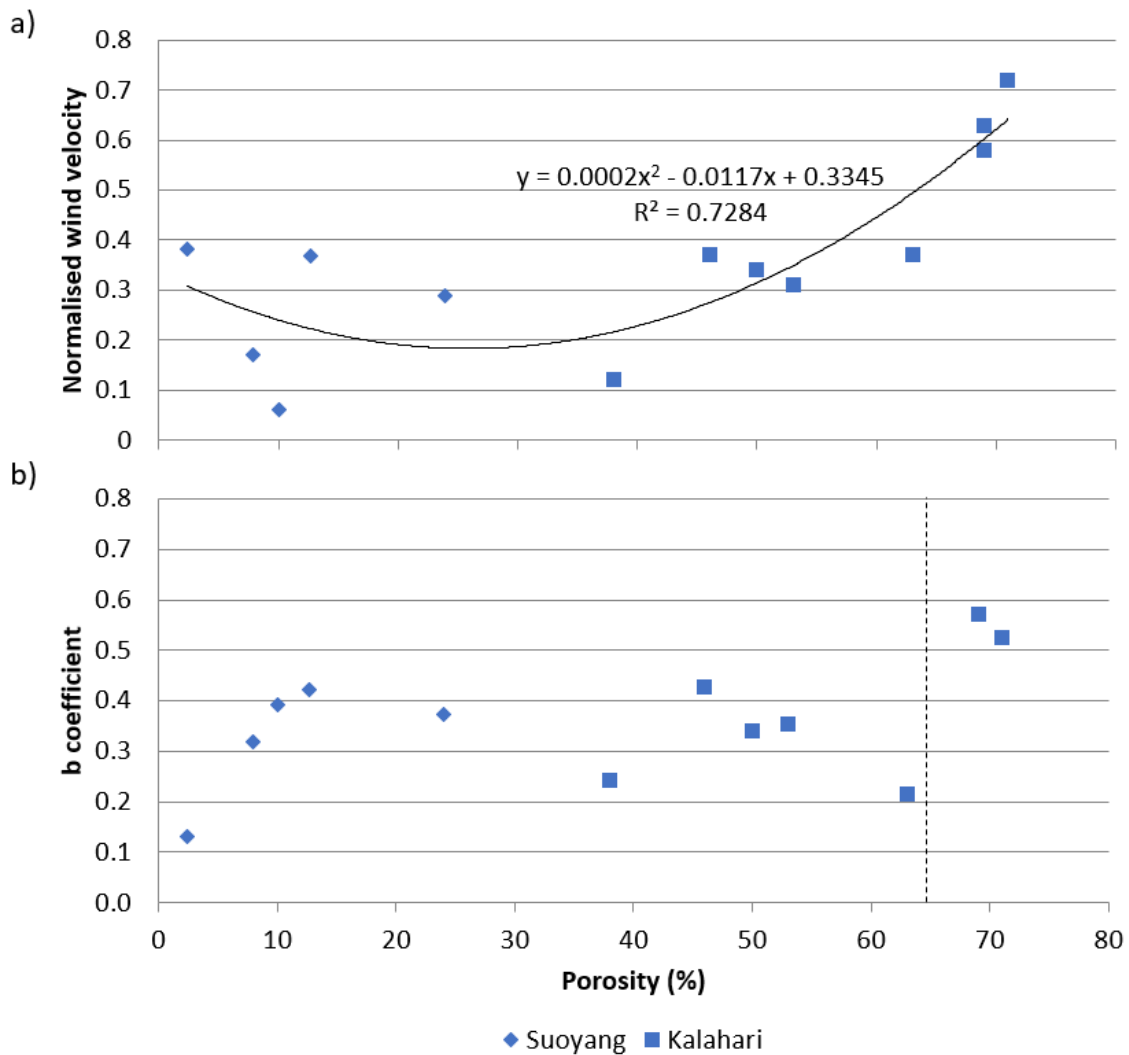


Figure C.2: The relationship between porosity and a) the mean normalized minimum wind velocity, and b) the b coefficient using the joint Kalahari-Suoyang dataset.

C1.1.3 Wind flow round earthen walls

Solid structures, such as earthen walls, alter wind flow (Richards et al., 2001; Tsoar, 1983). To understand the impact of earthen heritage on wind flow, wind velocity measurements were taken 50 cm above the ground around the Suoyang test walls. The measurements showed that the extent to which the wind was laterally accelerated around the walls was strongly dependent on the location of the wall to other walls and the approach angle of the wind (Figure C.3). When the wind flow was travelling between two walls, the lateral acceleration was notably greater than when it was travelling around a wall edge that did not have another wall within 2 m, owing to airflow

compression (Garvey et al., 2005; Richards et al., 2001). The acceleration was greatest when the wind direction was perpendicular to the wall (0°) and decreased linearly as the wind direction became more acute to the wall face (Figure C.3). These linear regressions were used to parameterize the acceleration of wind velocity around the walls in ViSTA-HD.

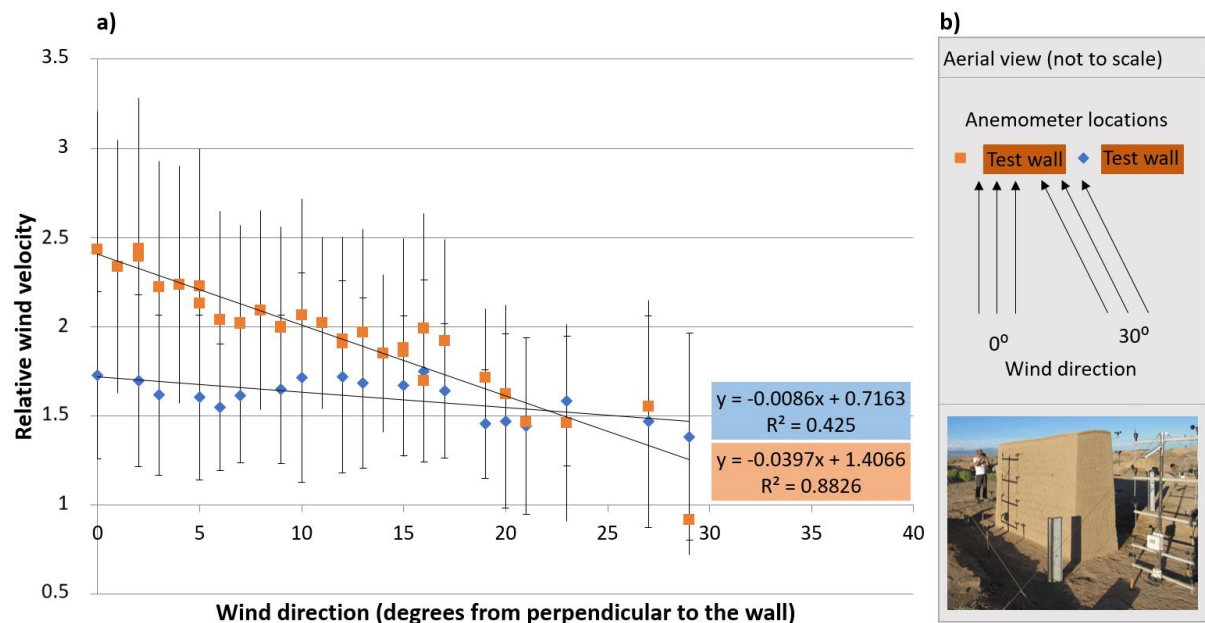


Figure C.3: a) The relationship between wind direction and relative wind velocity at two locations shown in b). The relative wind velocity is calculated according to the wind velocity at 1 h upwind of the wall (where h is the height of the wall).

C.1.1.4 Sediment transport

The presence of solid structures also affects sediment transport. Unlike plants, where their lower porosity enables some sediment to travel through the element (Mayaud et al., 2017a), solid objects can act as a trap, resulting in the formation of dunes in front of such objects (Rowell et al., 2018; Tyson, 1999).

In ViSTA-HD, sediment transport pathways are always modelled as following the simulated wind direction, because sediment transport does tend to align with wind direction in field studies (omitting small-scale processes such as sand snakes and minor

recirculation zones) (Anderson et al., 1991; Gares et al., 1996; Goossens and Offer, 2000; Sherman and Hotta, 1990). Tests using smoke flares around the test walls at Suoyang revealed that wind flow gets deflected around wall faces (Figure C.4), so in the model, sediment transport pathways that come into contact with wall faces are deflected sideways accordingly.

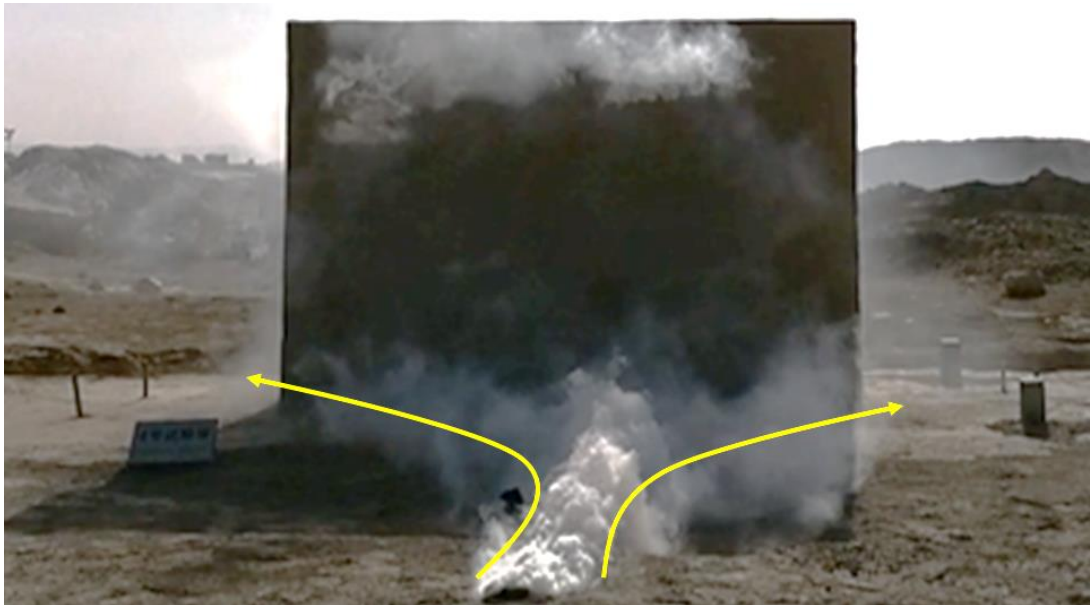


Figure C.4: A photograph of the flare experiment showing the deflection of the wind flow around the test wall.

C1.2 Parameterizing the deterioration module

Environmental data from Suoyang was also used to inform the environmental conditions occurring across the wall face in the deterioration module. As wind velocity is resolved at 50 cm above the surface, the wind velocity determined by the environmental modules is imputed into the deterioration module at 50 cm above the surface. Due to the different cell resolutions in the environmental (1 m) and deterioration (0.25 m) modules, the inputs from the environmental module are inputted into deterioration module cells which align centrally with the environmental module cells (Figure C.5). Conditions at 50 cm above the surface are linearly interpolated where appropriate (see Figure C.5b for example).

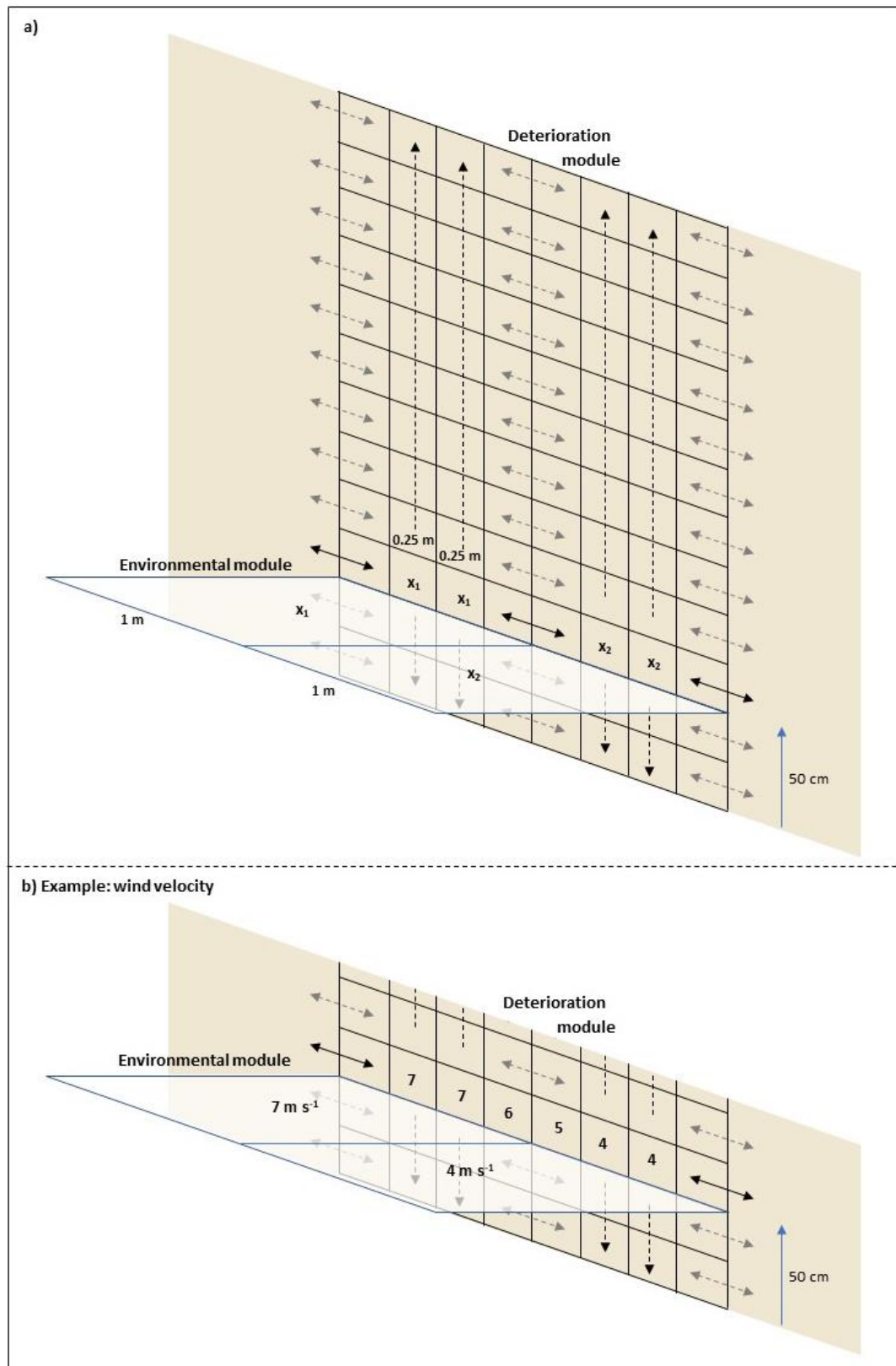


Figure C.5: a) The interaction of the environmental and deterioration modules at the wall face: x_1 and x_2 represent environmental conditions resolved in the environmental module. The solid black arrows show interpolation between inputs. Dashed vertical arrows indicate the extrapolation of conditions above and below the environmental input and the dashed horizontal arrows indicate the interpolation between calculated conditions across the wall face. b) An example of wind velocity inputs from the environmental module into the deterioration module.

Wind towers located 0.5 m away from the test wall, with cup anemometers located at 0.2, 0.5, 1, 1.5 and 2 m above the ground, were used to determine how wind speed changed with height up the wall face (Figure C.6a). As the historic walls at Suoyang can be much taller than the 2 m test wall, the dataset was fitted with an exponential curve, such that the rate of increase in wind velocity decreased with height.

A wedge-shaped sediment trap (90 cm tall made up of 2 cm increments) located 1 m upwind of the test wall was used to determine how sediment transport varies with height. The trap was deployed for one month after which the mass of sediment in each increment was measured in the laboratory using an Ohaus mass balance with 0.01 g precision (Figure C.6b). We observed that sediment volume decreased with height between 0 and 40 cm above the surface, above which the volume of sediment remained constant at all heights. We therefore consider the saltation zone to occur within the first 40 cm above the surface, similar to Dupont et al. (2013) (as shown by the dashed line in Figure C.6b).

These parameterized environmental conditions across the wall face were used to inform the environmental risk of polishing, pitting and slurry across the wall face (see Figure 6.5 in the main paper for further details).

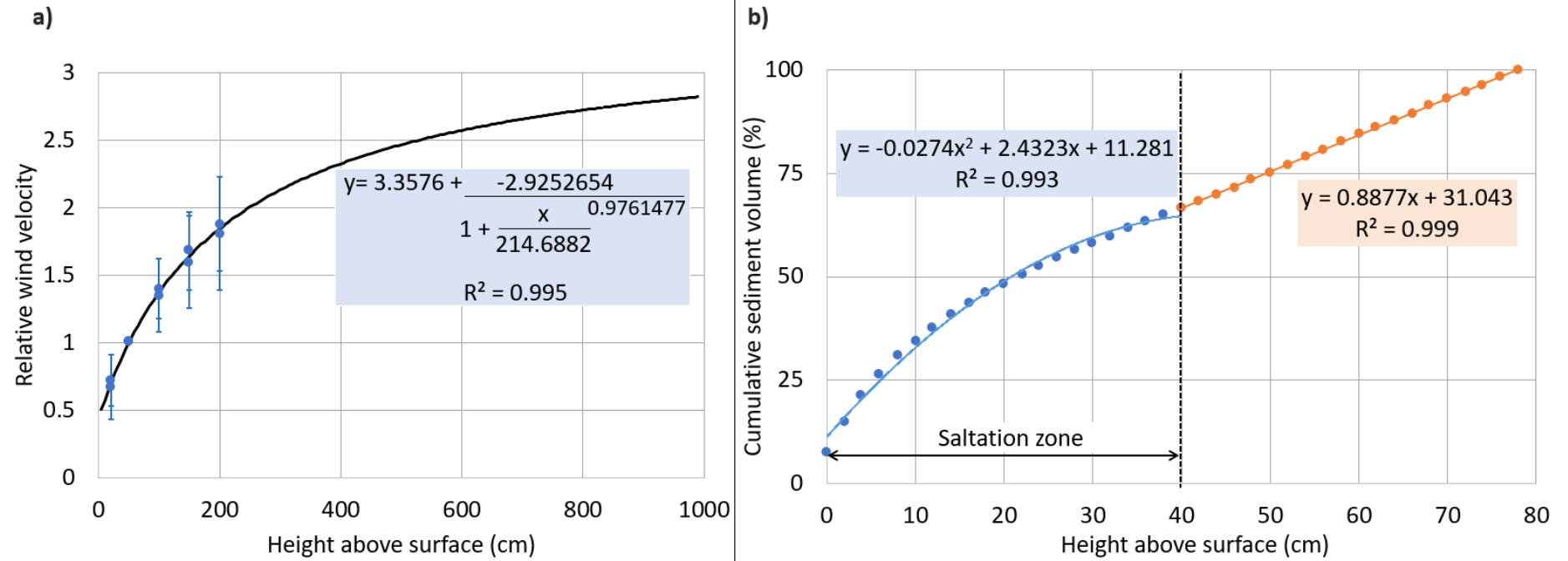


Figure C.6: Change in a) wind velocity (relative to the wind velocity 0.5 m above the ground), and b) total volume of transported sediment, with increasing height from the ground. The dashed black line in b) indicates the determined height for sediment transport occurring within and above the saltation zone.

C.2. Model verification

C.2.1 Environmental module

C.2.1.1 Climatic inputs

Environmental and deterioration processes within ViSTA-HD are driven by wind velocity, sediment availability and rainfall.

Wind velocity data (shown in Figure C.1) was used to inform the wind regime inputted into ViSTA-HD. Since low wind velocities are unlikely to pose a deterioration risk, rarely entrain sediment (Dong et al., 2003), and are commonly interspersed with greater gusts of wind, we disregarded periods in the dataset when wind velocities dropped below 4 m s⁻¹. We used the remaining data to derive seasonal probability density functions that drive wind velocity the environmental module. In each iteration, a wind velocity was randomly selected from the probability density function to provide an unobstructed wind velocity (u_{ref}) that represents the mean flow over flat surfaces. The unobstructed wind velocity was held constant for the duration of each iteration. To capture the stochastic nature of airflow, a stochasticity function developed by Mayaud et al. (2017a) was applied to wind flow in ViSTA-HD enabling variation in wind velocities between identical cells (see Mayaud et al. 2017a for description).

After running ViSTA-HD for 200 iterations, the modelled wind velocities were visually compared to the wind velocities recorded at Suoyang (Figure C.7). There was good agreement between the modelled and recorded wind velocities. The seasonal variations were captured with, for example, the strongest winds occurring in the summer and westerlies becoming more dominant in autumn and winter (Figure C.7). This enables the

environmental processes modelled within ViSTA-HD to be reflective of those occurring at Suoyang over both annual and seasonal timescales.

Historic rainfall data provided by the Dunhuang Academy showed that between 1986 and 2005, the average annual precipitation was 49.2 mm, ranging between 33.6 mm and 74.2 mm. The average seasonal rainfall over this period was 6 mm, 12 mm, 25 mm and 6 mm for winter, spring, summer and autumn respectively. The maximum recorded daily rainfall in this period was 30.7 mm. In addition, a limited rainfall dataset collected at the site between March and December 2018 was also used to inform the frequency of rainfall events. This data was used to parameterize the rainfall within ViSTA-HD (Figure C.8).

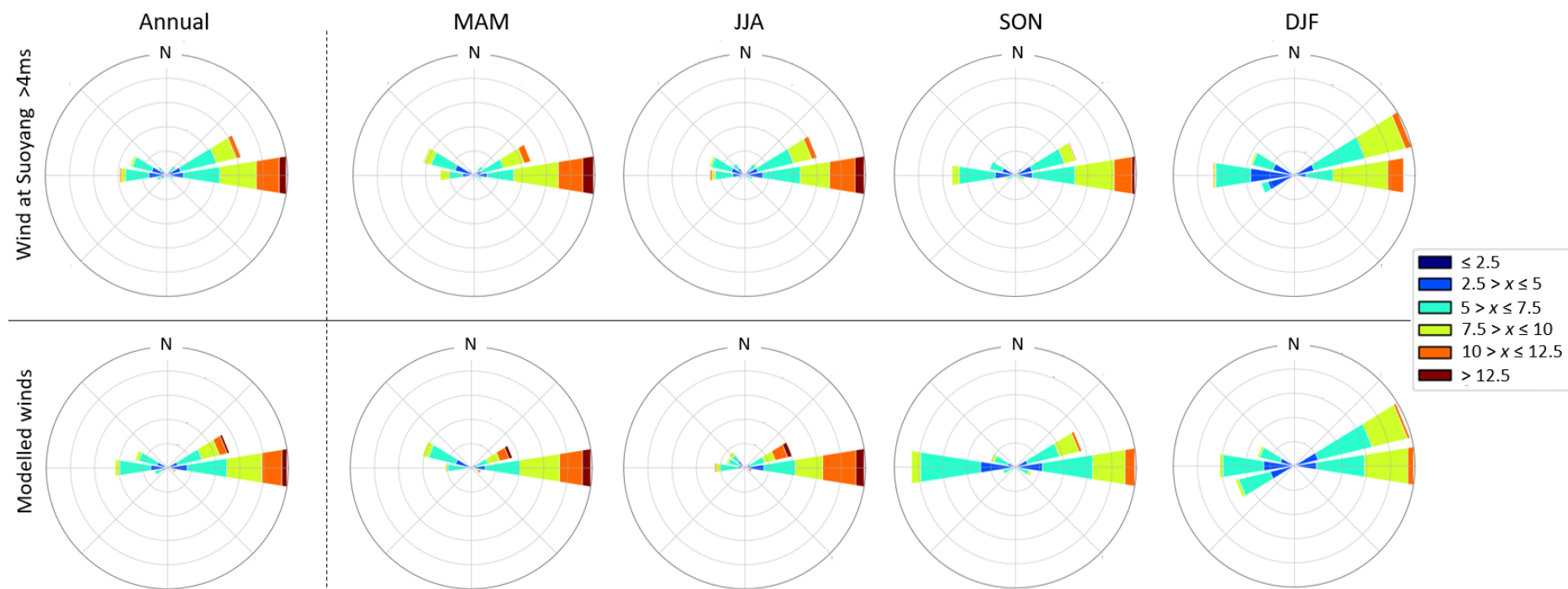


Figure C.7: Wind roses comparing the wind regime above 4 ms⁻¹ at Suoyang to the wind velocities inputted into ViSTA-HD.

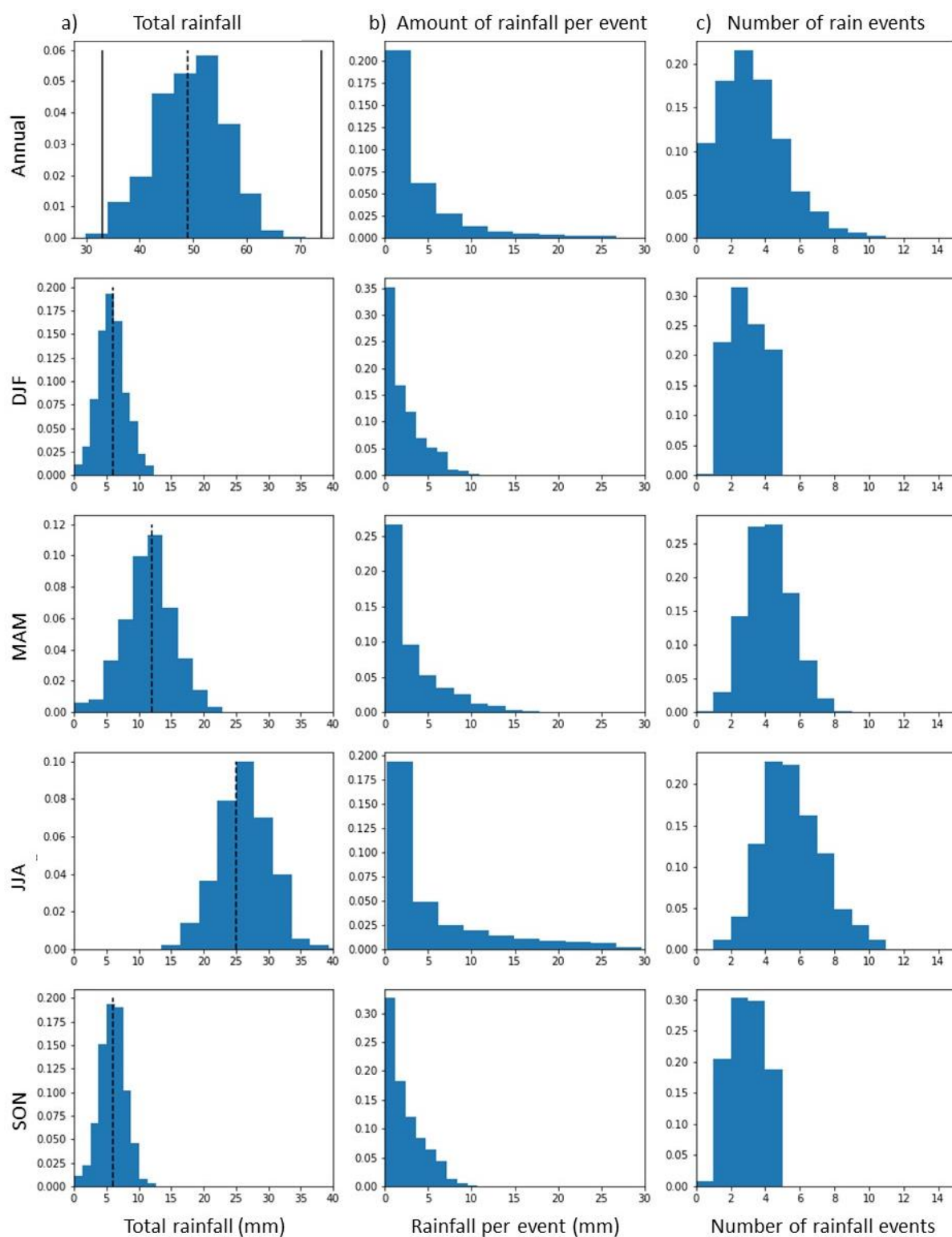


Figure C.8: a) Total rainfall, b) quantity of rainfall in each storm event, and c) the number of rain events per iteration, over an annual time period and for each season (DJF, MAM, JJA, SON) individually. The dashed black lines in the first panel show the mean annual rainfall and the solid black lines shown the minimum and maximum annual rainfall.

C.2.1.2 Wind flow dynamics

Laboratory studies (Tsoar, 1983) and results from Suoyang found that wind velocity begins to decelerate at $3 h$ (where h is the height of the wall) upwind of a wall. In addition, lateral acceleration around the walls was observed at Suoyang (Figure C.3) and wind velocities downwind of the wall recovered within $15 h$. ViSTA-HD is able to capture these interactions between earthen walls and wind flow, with taller walls having longer upwind turbulence zones as well as a longer downwind shadow zones (Figure C.9).

C.2.1.3 Sediment transport

At Suoyang, earthen walls can act as a sediment trap allowing the development of dunes around the walls. To verify that the walls present within ViSTA-HD were able to act as a sediment trap, the model was run for 300 iterations, with 1.5 m of sediment in all grid cells and no vegetation coverage, with winds alternating west-north-west and west-south-west. Dune features developed in front of both the long and short walls (Figure C.10). It is notable that the dune in front of the longer wall was more persistent, which reflects dunes observed at Suoyang where sediment is transported around shorter wall sections.

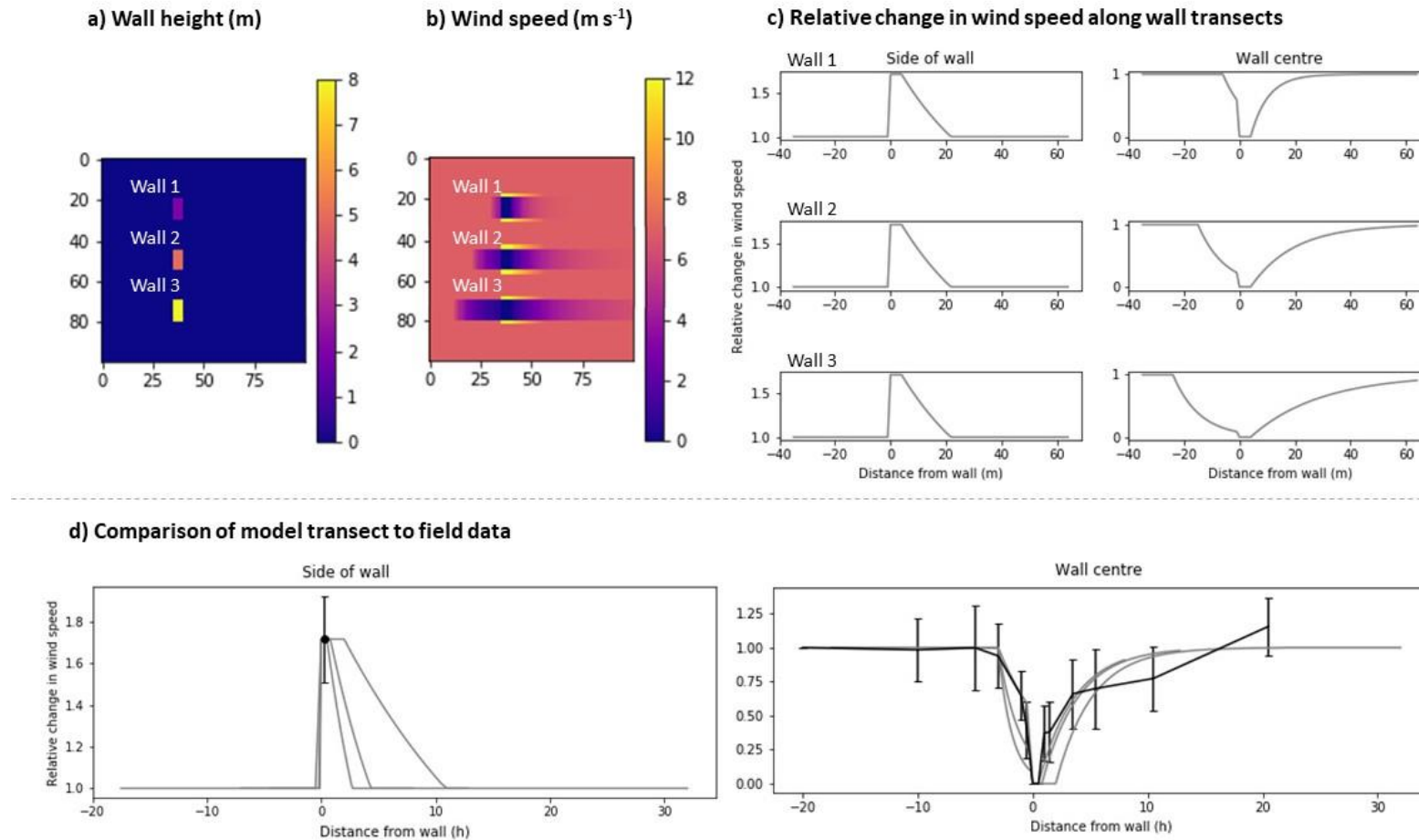


Figure C.9: A comparison of the modelled wind flow around three walls of different heights (3, 5 and 8 m) with data collected from Suoyang: a) Location and heights of the three modelled walls; b) wind velocity across the model space caused by a wind blowing from left to right; c) transects of wind velocity to the side of the wall where acceleration occurs and through the centre of the wall; d) comparison of modelled wind velocities (grey) to wind velocities collected at Suoyang (black). The distance from wall is reported in h (where h is the height of the wall), to enable comparison between model and field data. Error bars show one standard deviation from the mean

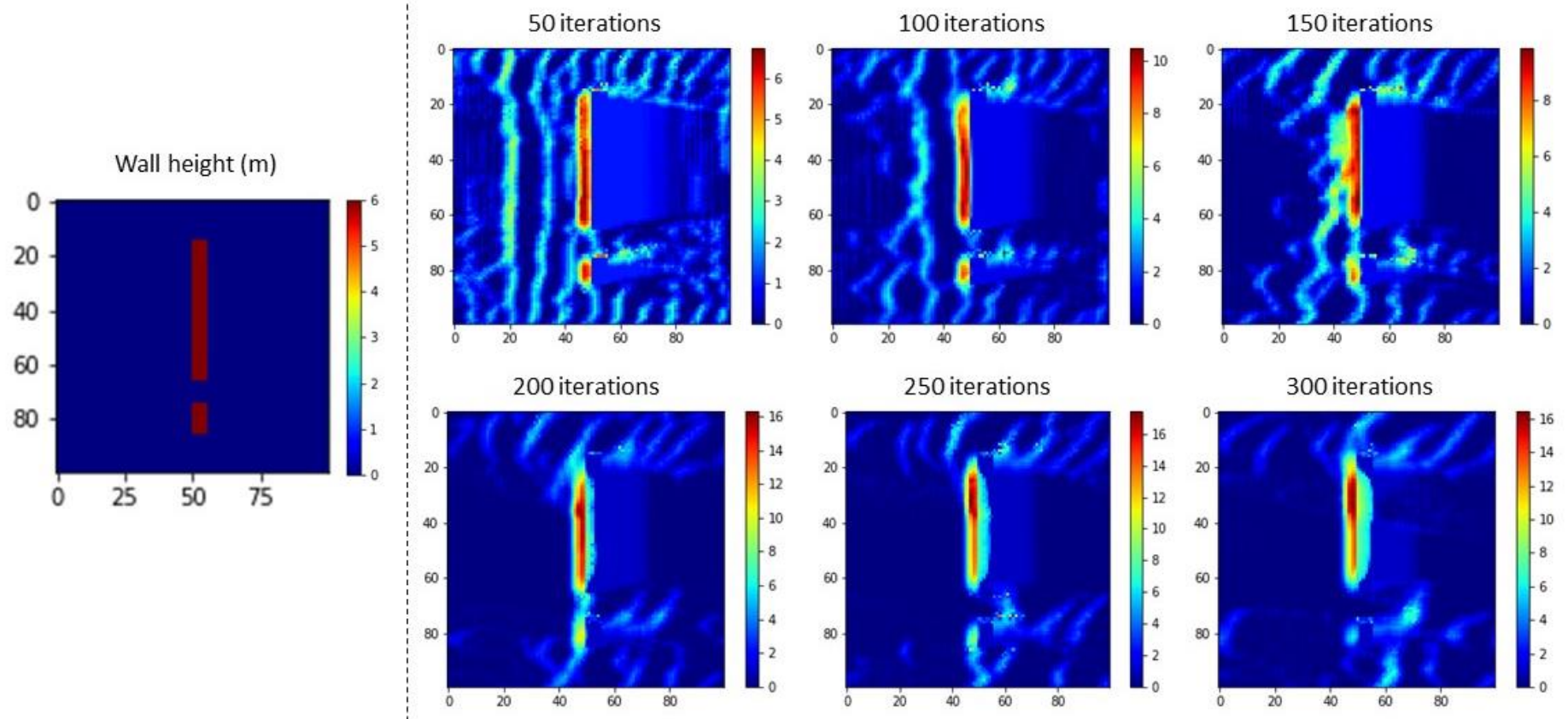


Figure C.10: The development of dunes in front of two walls (measuring 50 m and 10 m in length and 6 m in height), over 300 iterations.

C.2.1.4 Dune dynamics

To further verify the development of dunes within ViSTA-HD, the morphology of modelled dunes was compared to those found at Suoyang in four different model setups: (i) two short walls (10 m in length) located close together; (ii) a long wall (40 m) and a short wall (10 m); (iii) two long walls (80 m) with one placed downwind of the other; (iv) and a long wall (40 m) and a short wall (10 m) with 80% vegetation cover (Figure C.11). Dune morphology was assessed using measurements that could be taken both in the model and in the field. The height of the exposed wall face and the length of the dune on the upwind side of the wall were compared at the end of each model run.

Each model setup was initially inputted with environmental conditions reflective of seasonal variations observed at Suoyang (Figure C.7Figure C.8). Each model setup was run for 500 iterations (representing 125 years in real time) and repeated 10 times.

Proportional histograms were created to display the range in the height of the exposed wall face and the length of the modelled dunes (Figure C.11). The measurements taken from the dunes at Suoyang were categorized by wall length (short walls < 10 m, long walls > 10 m) and vegetation (<70%, > 70% vegetation coverage) and were overlain on the modelled results with black triangles (Figure C.11).

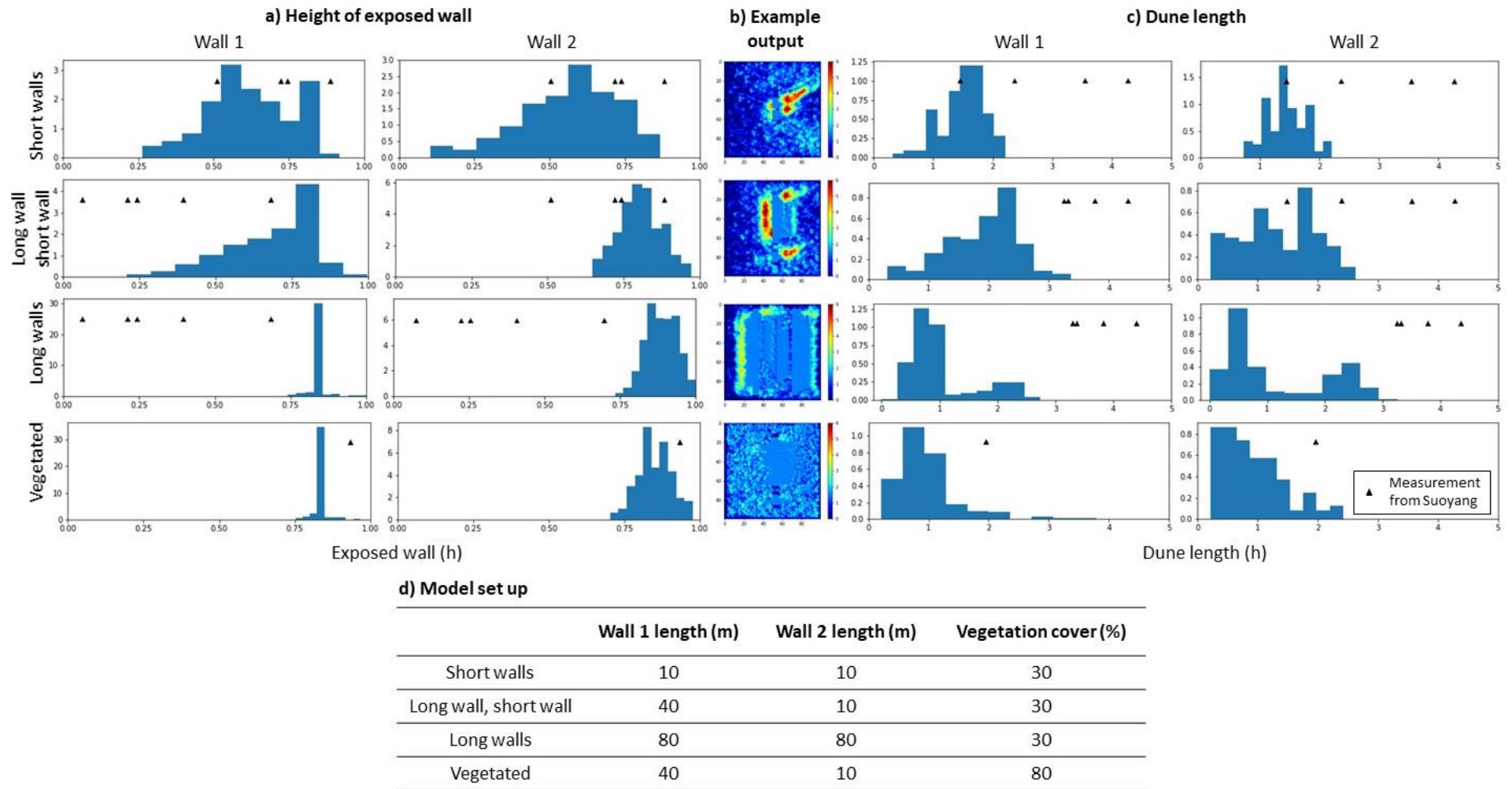


Figure C.11: Comparison of modelled and real dune morphologies on the upwind side of walls. The range of dunes morphologies are shown using histograms for the modelled dunes and triangles for the measurements taken in the field. Four model configurations were used to compare a) the height of exposed walls and c) the dune length. An example of each model configuration after 500 iterations is shown in b). The model set up is shown in d).

The height of exposed wall for the modelled dunes corresponded well with the dunes measured at Suoyang, except for dunes located in front of the long walls. The development of the dunes in front of the two long walls was limited by the total number of iterations run in this experiment, which suggests that dunes in the field are likely to have developed over a longer period of time than represented by the model run. For all set up conditions, the model runs did not capture the longer dune lengths. The lack of shorter dune measurements may have been influenced by a sampling bias in the field, as we only chose to sample walls which had notable upwind dunes. The dune lengths may also be influenced by varying climate regimes that are not captured within the model. Nevertheless, the modelled dune lengths are generally within 1 or 2 h of the dune lengths measured in the field, which we consider acceptable for the purposes of this model.

Given that desert surfaces are rarely truly flat, the sensitivity of sediment build-up to surface topography was tested in ViSTA-HD. We used the same wall configuration as presented Figure C.10, and two model setups were compared: one with an initial uniform 1.5 m layer of sediment, and the other with a pre-conditioned surface. The pre-conditioned surface was initialized by running the model for 500 iterations, removing the dune formations before the walls, and then equally distributing this sediment across the entire model space. For both the uniform and pre-conditioned starting setup, ViSTA HD was run 10 times for 500 iterations and the height of the exposed walls and length of dune for the upwind side of the wall were calculated (Figure C.12).

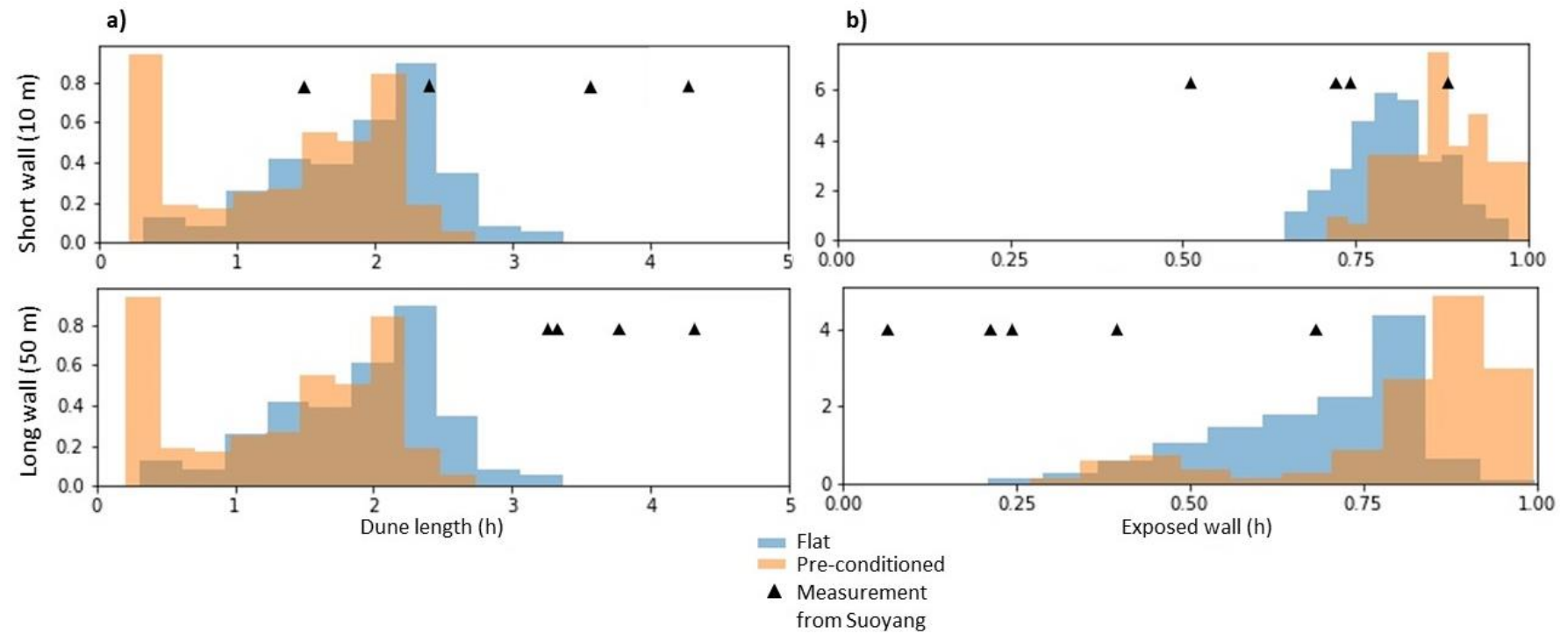


Figure C.12: Comparison of dune morphologies between models starting with a uniform (flat) sand height and a pre-conditioned surface for a) dune length and b) exposed wall where h is the height of the wall.

On the flat model runs, the uniform distribution of sediment covered the lower 1.5 m section of the wall, whereas this layer had been removed in the pre-conditioned, resulting in a greater proportion of the wall surface being exposed (although the similar distribution shapes suggests the difference between setups may not be significant). Similarly, the dune length distribution was similar between model runs, except for the prevalence of short dunes in the pre-conditioned model runs. This is also caused by the removal of sediment in front of the walls. Therefore, given the similarities between the model runs, it is not thought to make a significant difference if the model is inputted with uniform or pre-conditioned starting sand heights.

C.2.2 Deterioration module

C.2.2.1 Rainfall impact

In-situ observations have shown that rainfall impacts entire wall faces at Suoyang: after storm events, entire wind-facing wall faces are damp (Figure C.13a) and entire wall face are marked by wind-driven slurry features (Figure C.13b). Therefore, in ViSTA-HD wind-driven rain was parameterized as occurring equally across the wall face.



Figure C.13: The impact of rain on a) test wall 24 hours after a storm event, and b) on the historic walls

C.2.2.2 Setup for sensitivity tests

To test the inherent variability of the deterioration module, the module was run multiple times with the same initial conditions until the mean and standard deviation of overall deterioration from the model runs had stabilized. Once the mean and standard deviation of the model runs has stabilized this suggests that additional model runs will not significantly alter the result. The mean and standard deviation of the overall deterioration for (i) the entire wall face and (ii) randomly selected individual cells was calculated (Figure C.14). The mean and standard deviations for both the entire wall face and individual cells stabilized after approximately 50 replicate model runs. Consequently, the environmental module should be run for a minimum of 50 repeats for each set of input conditions.

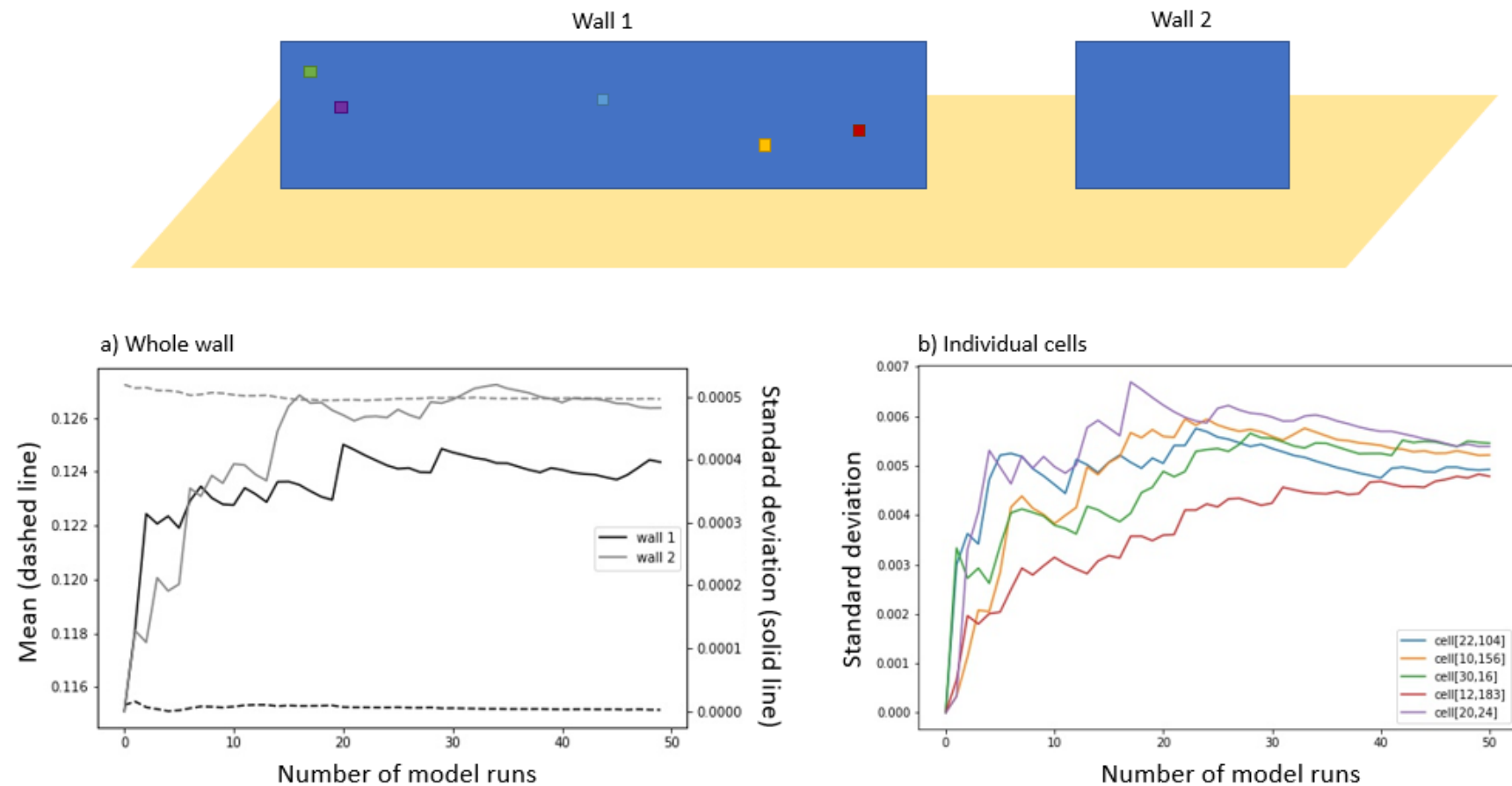


Figure C.14: The running mean for 50 repeat runs of the a) mean and standard deviation of the risk of deterioration across two wall faces and b) the standard deviation of the risk of deterioration in randomly selected individual cells. The approximate location of the individual cells are shown on wall 1.

C.2.2.3 Spatial scale

The spatial resolution of deterioration risk is constrained by the interpolation required between the deterioration and environmental module (due to different cell resolutions) and available computational power. With a resolution 0.02 m^2 the deterioration module is able to resolve the reduced risk of deterioration associated with compaction layers – seen in Figure C.15 with the evenly distributed stripes of reduced deterioration risk (L. Li et al., 2011; Shao et al., 2013). However, due to the high computational burden required, it was only feasible to model a 2.5 m section of the wall. Therefore, a resolution of $0.25 \times 0.25 \text{ m}$ was chosen for the deterioration module to balance computational expense with capturing smaller scale deterioration features.

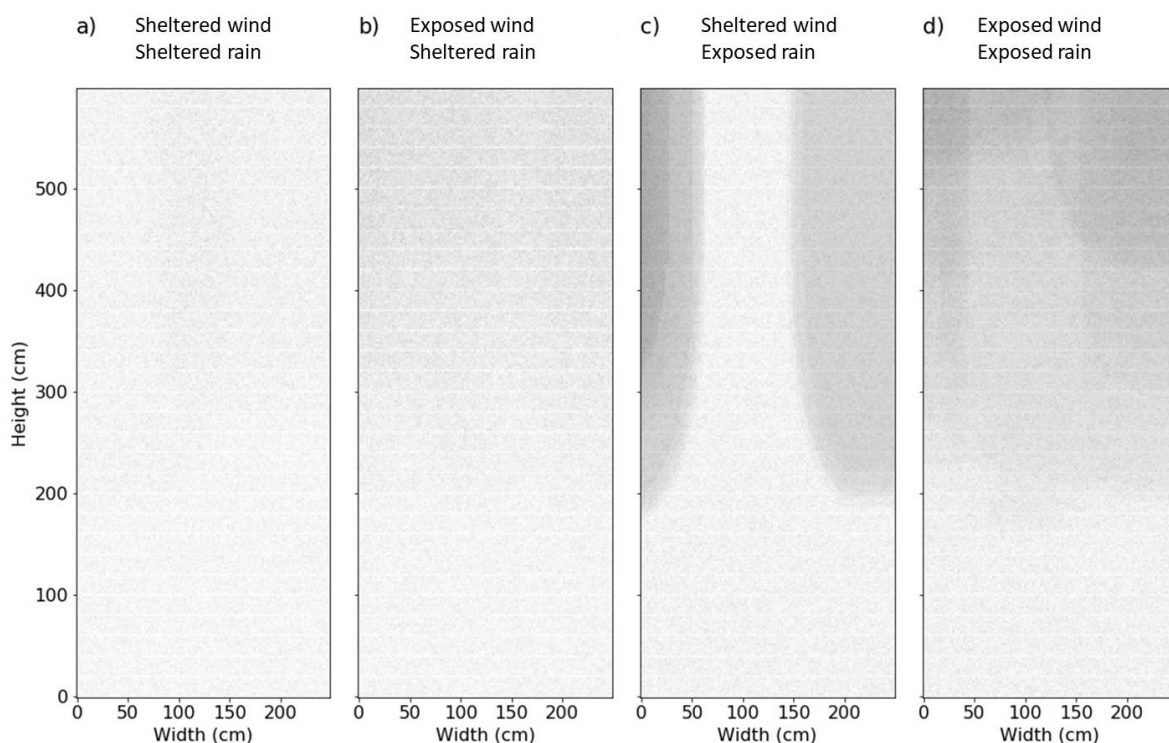


Figure C.15: Overall risk of deterioration modelled at 2 cm resolution on walls representing walls in locations a) sheltered from the prevailing wind and sheltered from rainfall, b) exposed to the prevailing wind and sheltered from rainfall, c) sheltered from the prevailing wind and exposed to rainfall and d) exposed to the prevailing wind and exposed to rainfall. Here, sheltered locations are modelled with a mean wind velocity of 5 ms^{-1} and the median rainfall event being 1 mm with an interquartile range of 1.75 mm. Exposed locations modelled with an average wind velocity of 12 ms^{-1} and the median rainfall event being 3 mm with an interquartile range of 8 mm.

C.3. Summary

The verification tests showed that ViSTA-HD can:

- Run simulations using climatic inputs that are representative of those occurring at Suoyang;
- Capture the wind flow and dune dynamics occurring around earthen walls;
- Capture environmental conditions occurring up a wall face and use these conditions to determine the environmental risk of deterioration.

Appendix D: Supplementary Material for Paper 4 (Chapter 7)

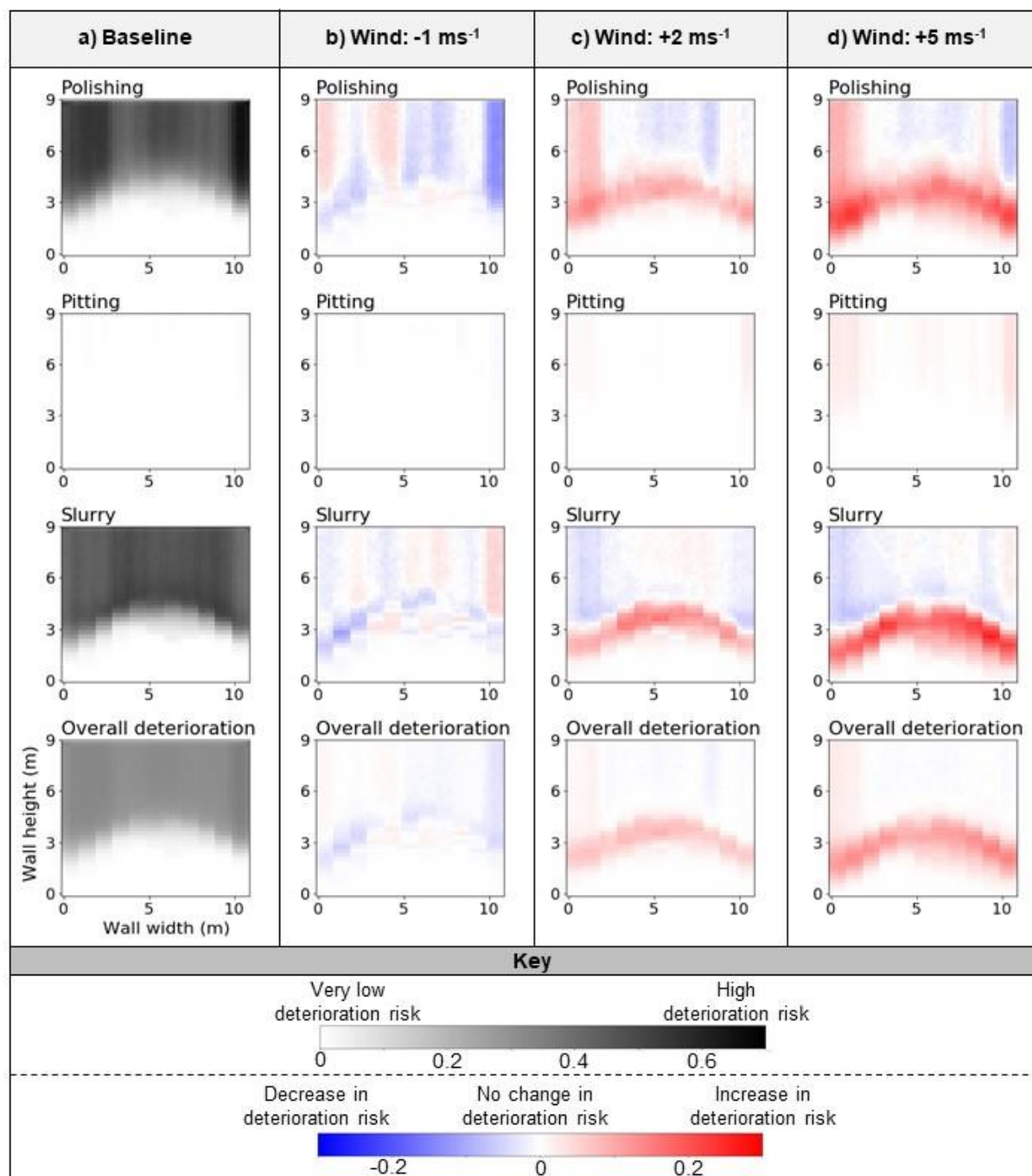


Figure D.1: The risk of polishing, pitting, slurry and overall deterioration after 100 years of model time on a 10 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 1 ms^{-1} decrease, (c) 2 ms^{-1} increase and (d) 5 ms^{-1} increase, in mean annual wind velocity.

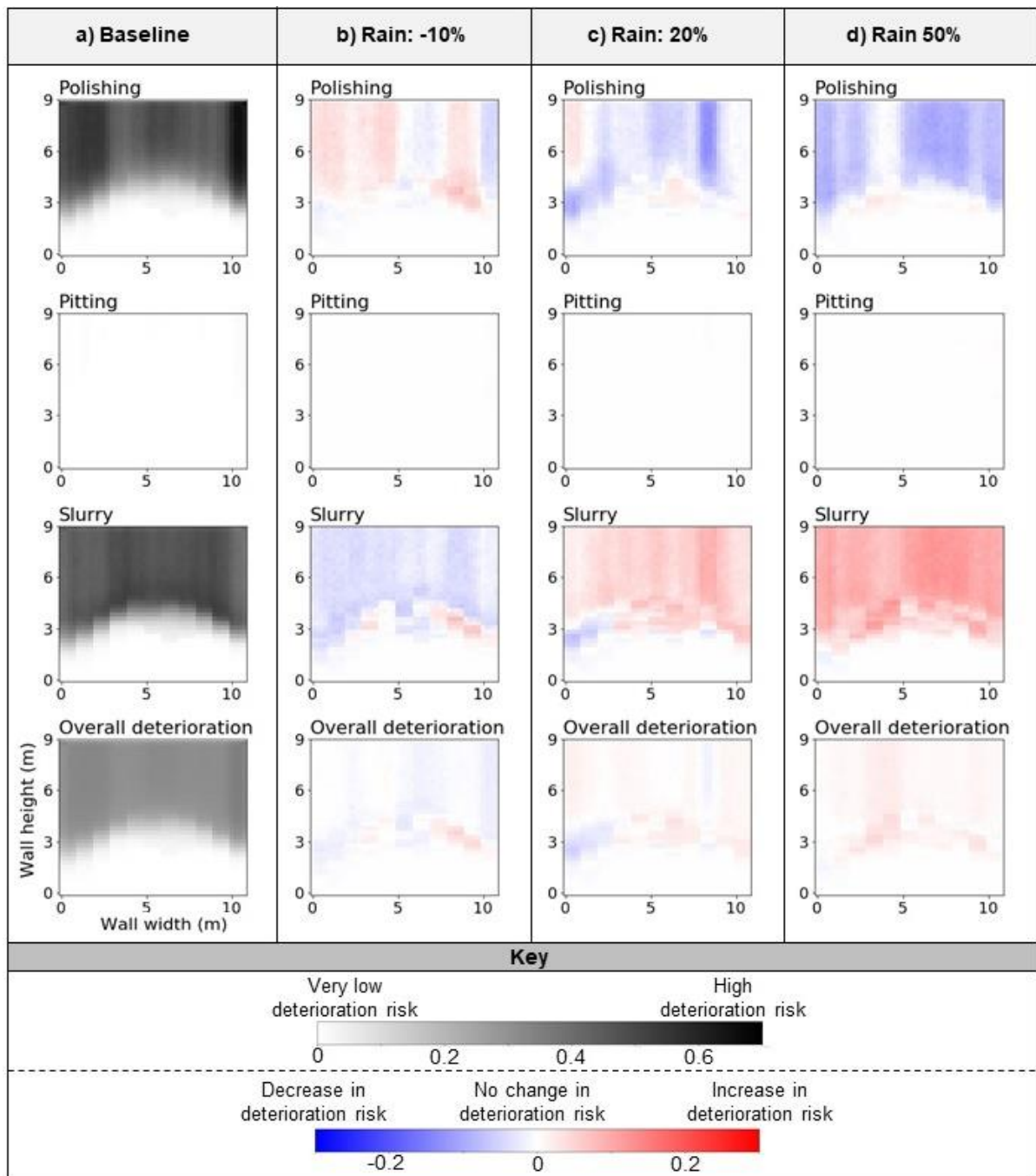


Figure D.2: The risk of polishing, pitting, slurry and overall deterioration after 100 years of model time on a 10 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 10% decrease, (c) 20% increase and (d) 50% increase in mean annual rainfall.

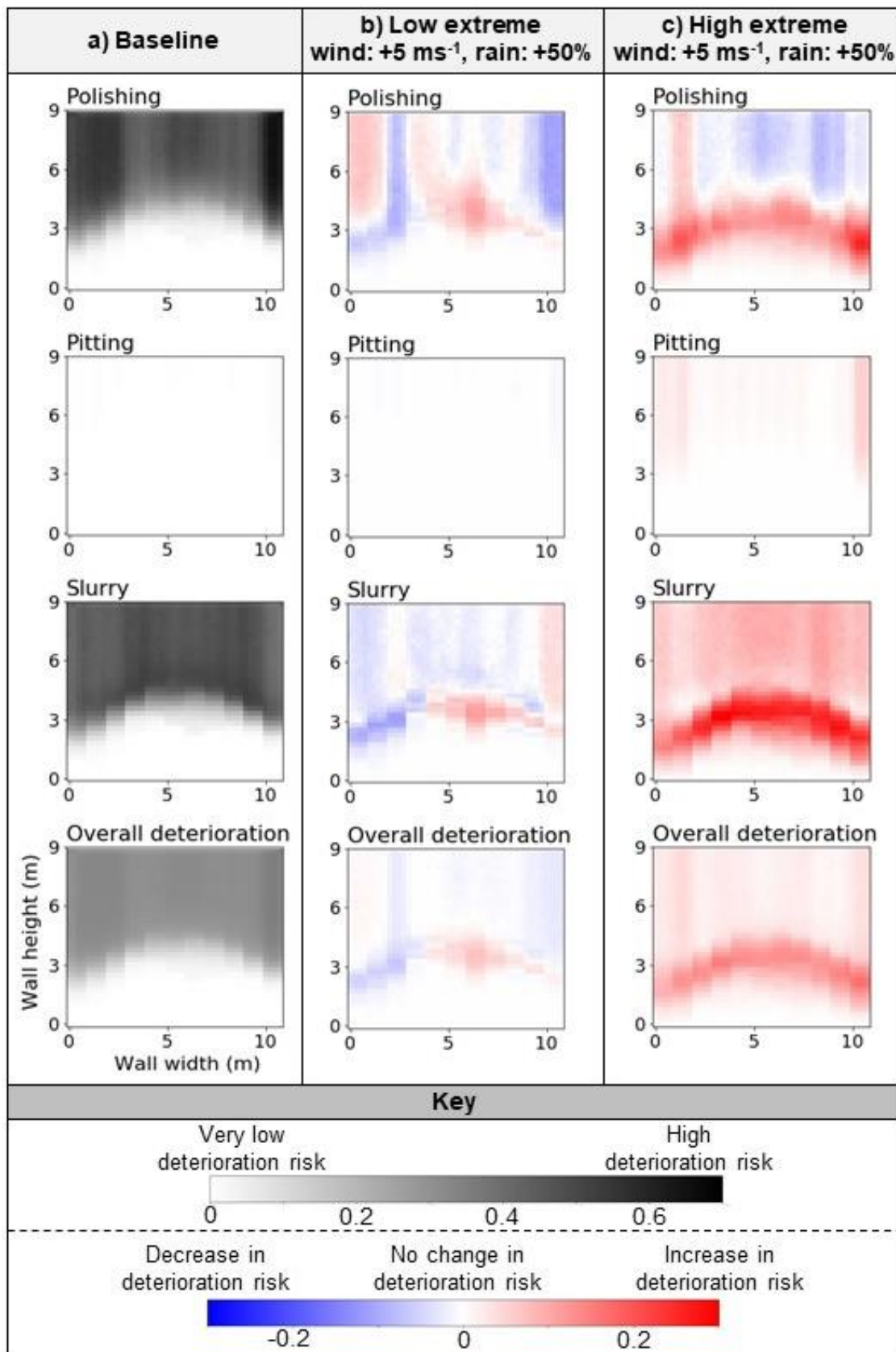


Figure D.3: The risk of polishing, pitting, slurry and overall deterioration after 100 years of model time on a 10 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 1 ms⁻¹ decrease and 10% decrease, (c) 5 ms⁻¹ increase and 50% increase, in mean annual wind velocity and mean annual rainfall, respectively.

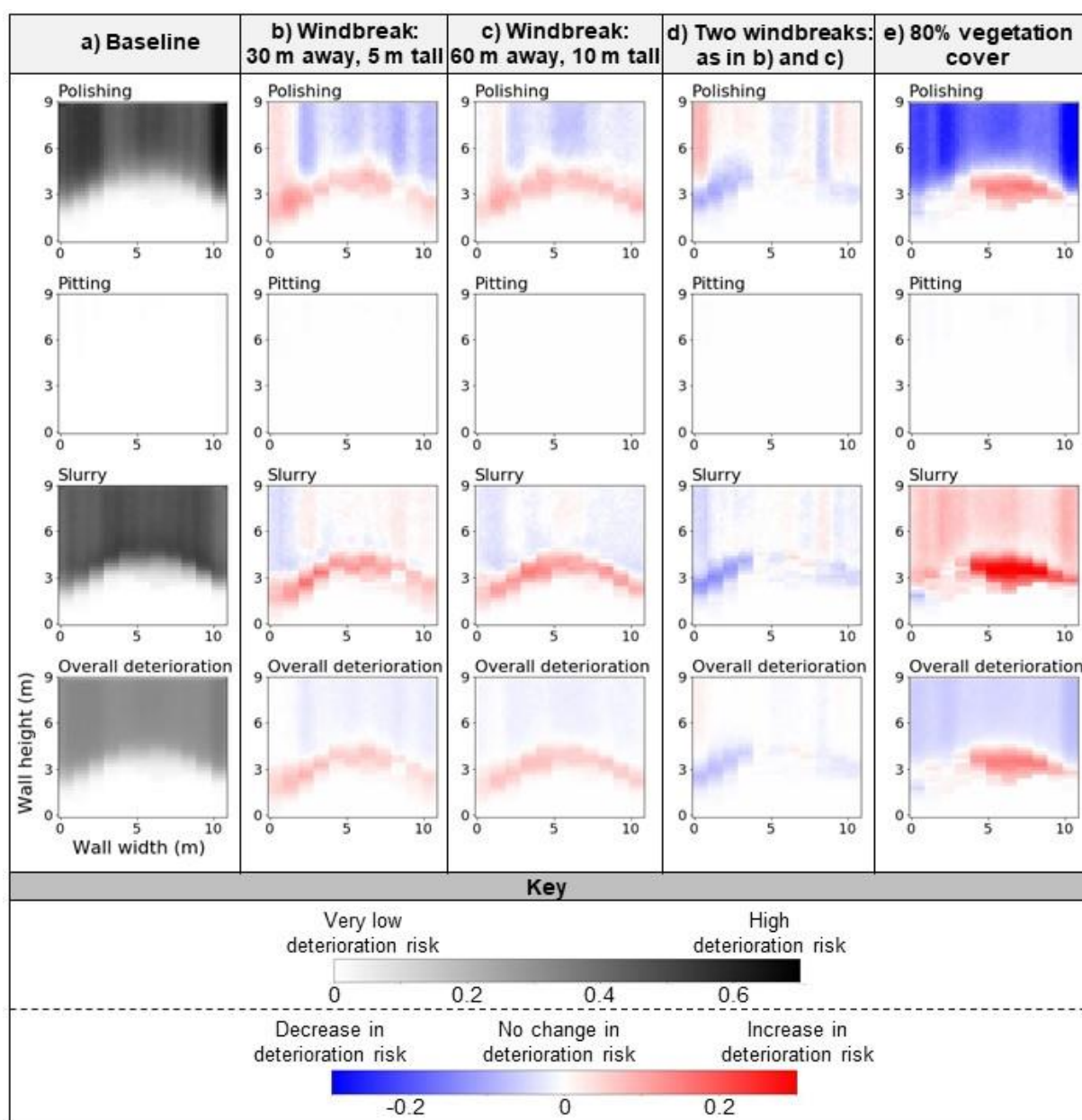


Figure D.4: The risk of polishing, pitting, slurry and overall deterioration after 100 years of model time on a 10 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from modelled conservation strategies (b) a near windbreak, (c) a far windbreak and (d) two windbreaks and (e) 80% vegetation coverage.

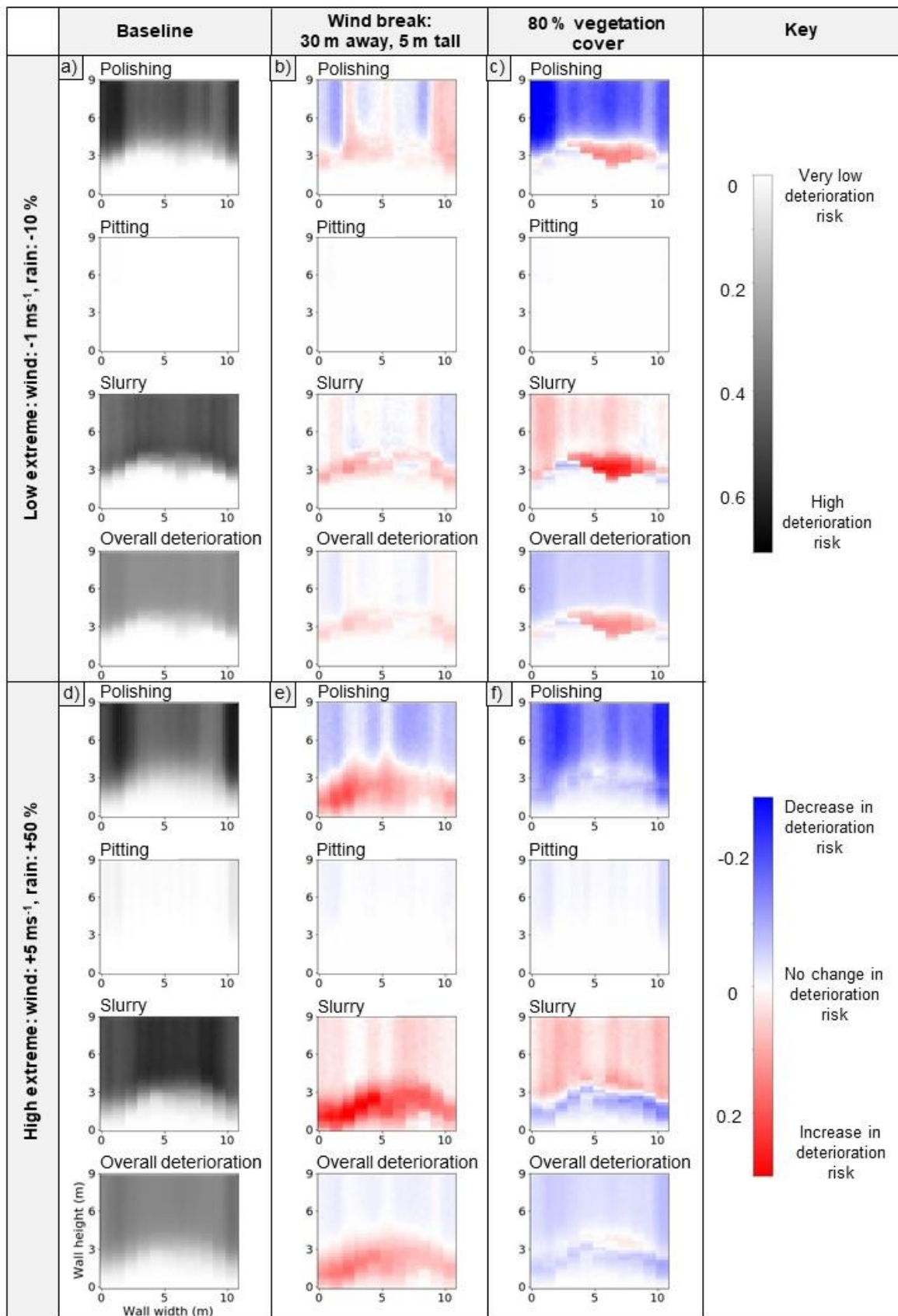


Figure D.5: The deterioration risk and difference in deterioration risk for polishing pitting, slurry and overall deterioration after 100 years of model time on a 10 m long wall, under (a-c) a regime of low mean annual windspeed and rainfall, and (d-f) a regime of high windspeed and rainfall. Different conservation strategies were applied: (a, d) no conservation strategy (baseline); (b, e) addition of a windbreak and (c, f) 80% vegetation cover.

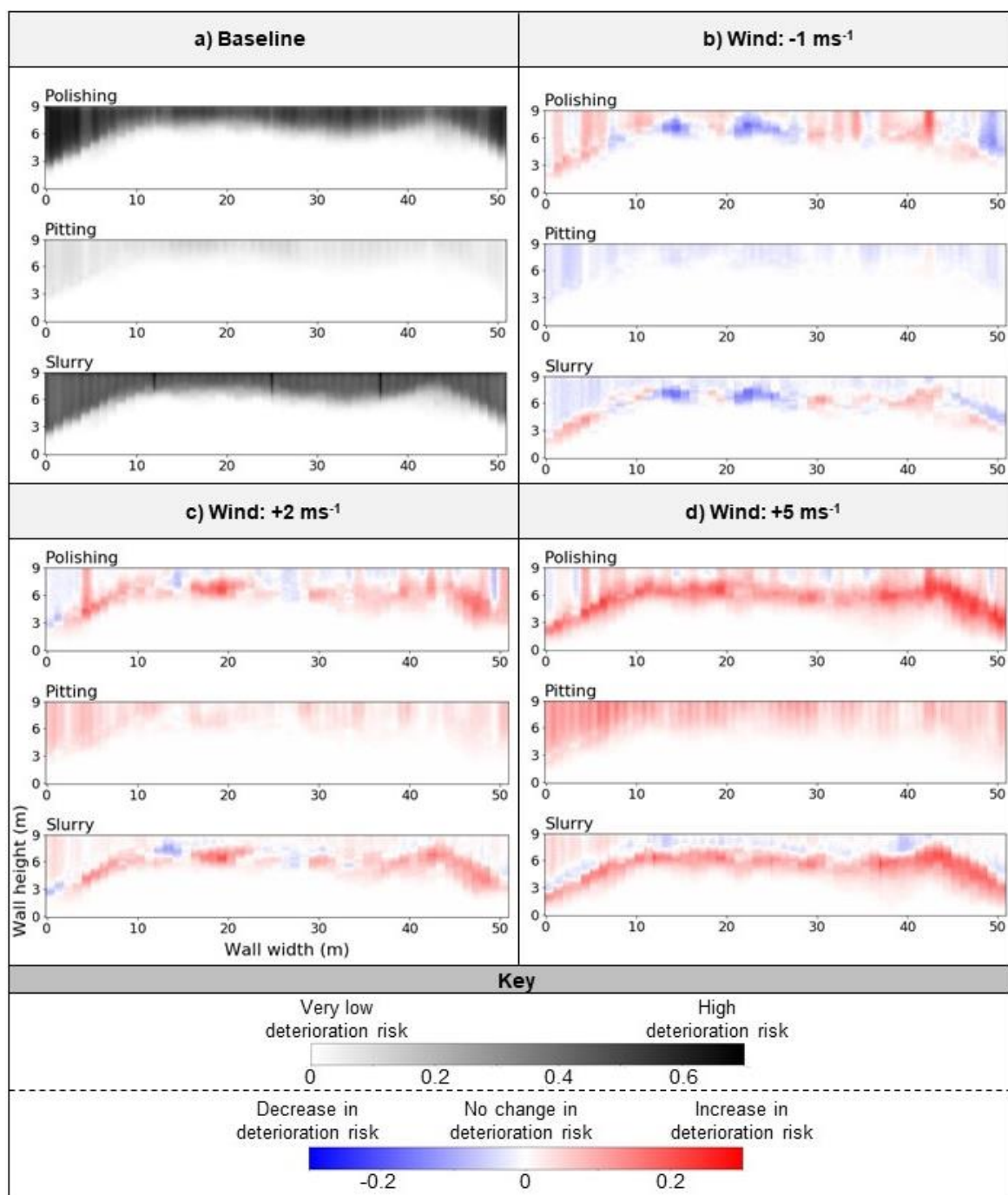


Figure D.6: The risk of polishing, pitting and slurry after 100 years of model time on a 50 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 1 ms^{-1} decrease, (c) 2 ms^{-1} increase and (d) 5 ms^{-1} increase, in mean annual wind velocity.

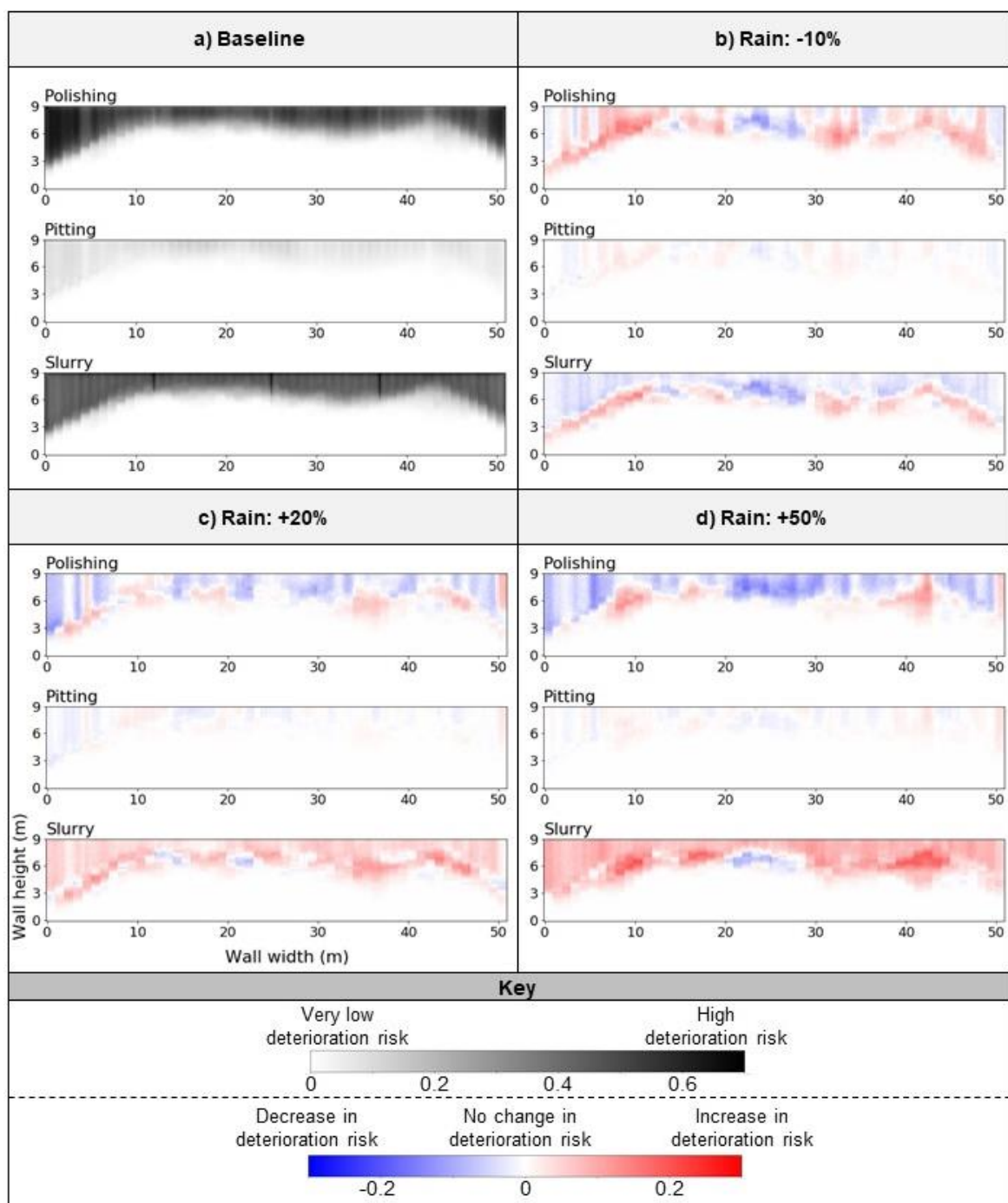


Figure D.7: The risk of polishing, pitting and slurry after 100 years of model time on a 50 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 10% decrease, (c) 20% increase and (d) 50% increase in mean annual rainfall.

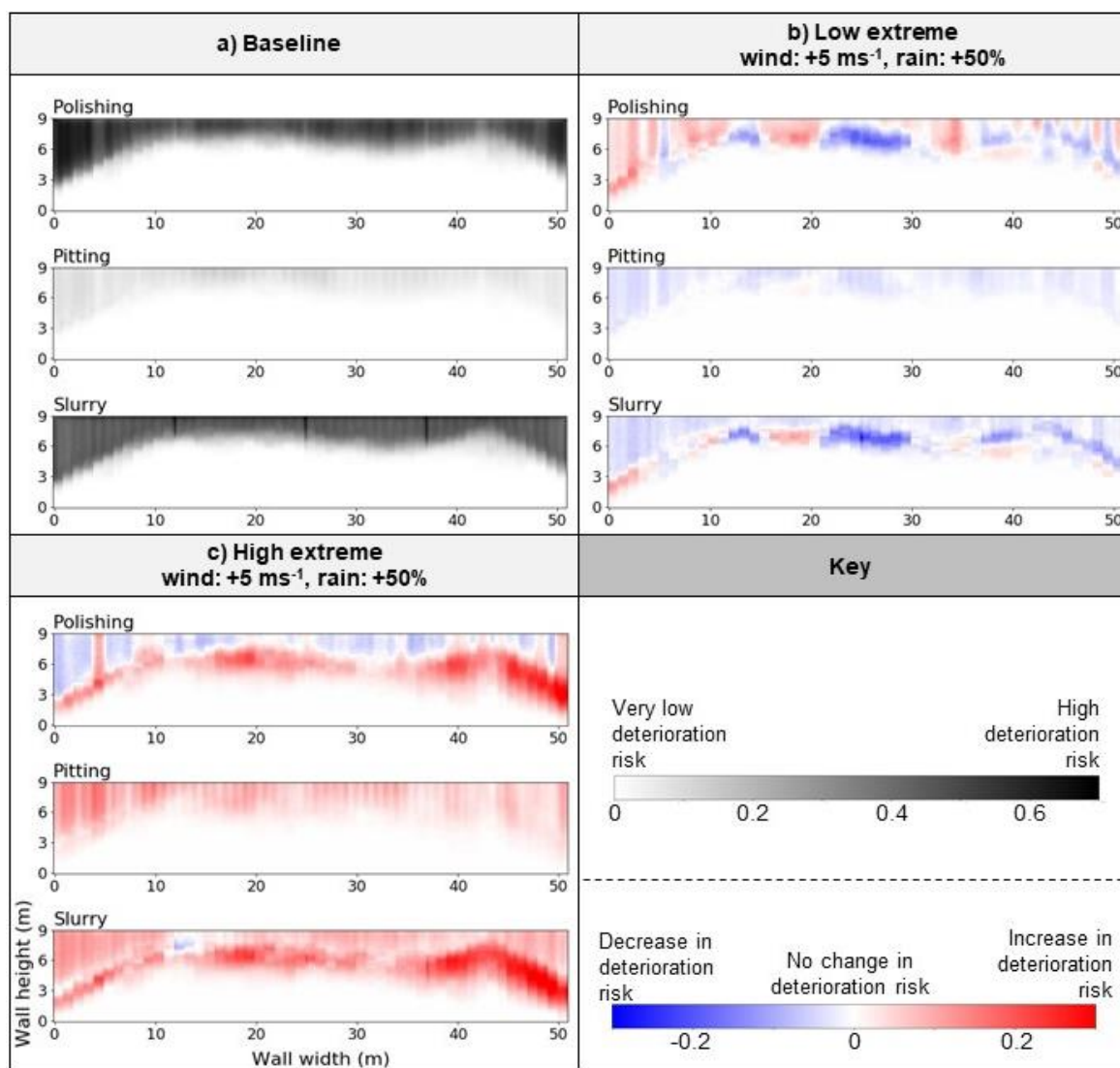


Figure D.8: The risk of polishing, pitting and slurry after 100 years of model time on a 50 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from a (b) 1 ms⁻¹ decrease and 10% decrease, (c) 5 ms⁻¹ increase and 50% increase, in mean annual wind velocity and mean annual rainfall, respectively.

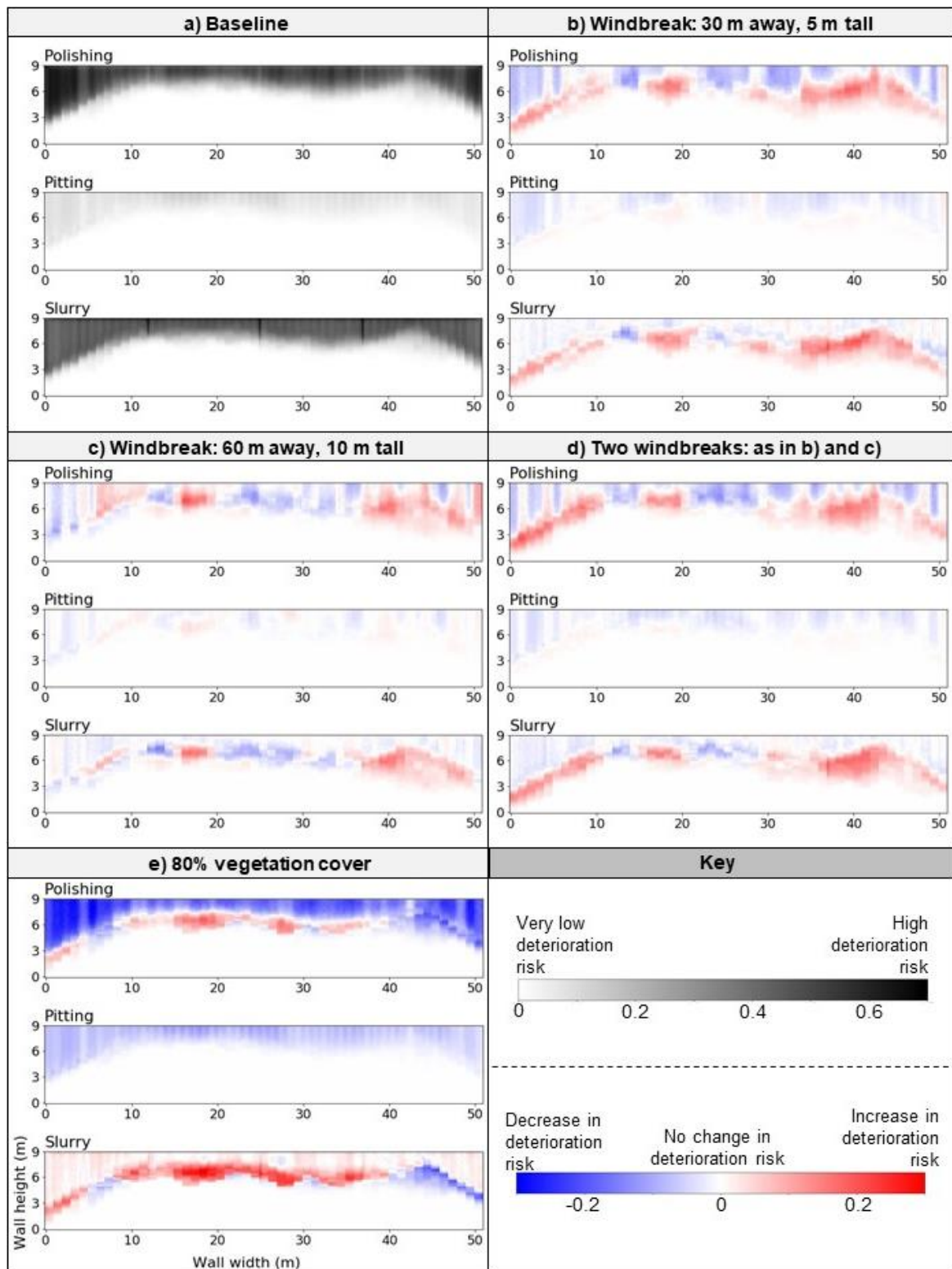


Figure D.9: The risk of polishing, pitting and slurry after 100 years of model time on a 50 m long wall, (a) under climatic conditions representative of those currently at Suoyang and (b-d) the resultant change in deterioration risk from modelled conservation strategies (b) a near windbreak, (c) a far windbreak and (d) two windbreaks and (e) 80% vegetation coverage.

Appendix E

Glossary: earthen heritage deterioration processes and features

Abrasion

Erosion of earthen material caused by entrained material (commonly sand) moving across the surface of the parent body of material.

Crack

A narrow, shallow fissure in the earthen material.

Crust

A thin surface layer of material that has formed over the parent body. It is commonly caused by rain-induced transportation and re-deposition of earthen material down with wall face and forms a harder surface layer.

Deflation

The removal of material by wind. This is also commonly referred to in other geomorphic literature as etching.

Entrainment

The process in which material becomes incorporated within a fluid flow (wind/ water).

Flaking/Scaling off

Thin surface features, usually several centimetres wide, that peel away from the surface and can create a scale-like pattern across the wall face.

Fracture

A larger fissure than a crack, with the fissure running the depth of the wall. Usually daylight can be seen through the gap.

Gully

An erosion channel caused by the flow of water down a wall structure due to gravity.

Hollow/Cavity

A hole present in a wall surface caused by the use of timbers during the construction process. Typically, the depth of the hole is greater than the diameter.

Outwash slope

A depositional feature caused by material entrained by water being deposited at the base of walls. Slopes range from centimetres to meters in height and width. Large slopes are commonly found below gully features and form conical shape.

Pitting

Irregular negative relief patterns typically emphasising the layering of rammed earth. The resultant surface is typically rough. In standard Western nomenclature, it is more commonly referred to as etching.

Polishing (wind and sand)

Areas of the wall face that have been smoothed by wind and sediment laden wind. They are often 'shinier' than the surrounding surface. Thin etched lines following the prevailing wind flow pattern can be seen on sand polishing areas.

Rounded corners

Edges of earthen walls smoothed by erosional processes.

Scouring at wall base

The removal of material at the wall base by entrained sediment. Scouring lines follow the wind flow around the base of the walls.

Slump

A mass movement where a large section of wall detaches from the parent body under gravity. In this thesis I consider a slump to occur when a section the height of the wall detaches itself from the parent body.

Slip

A mass movement where a small section of wall detaches from the parent body under gravity. Here, I consider a slip to occur when a section, smaller than the height of the wall detaches itself from the parent body.

Slurry

A surface feature commonly found on wall faces exposed to the prevailing storm direction. It is formed by moisture-induced transportation and subsequent deposition of material down the wall face, resulting in a sheet-like feature forming over the surface.

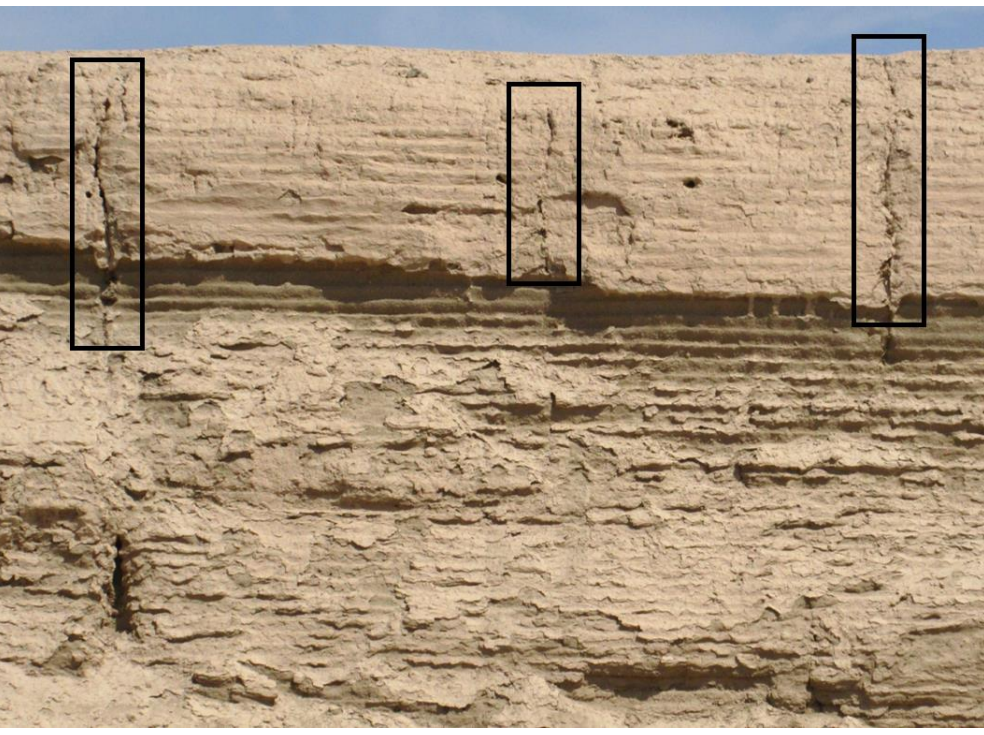
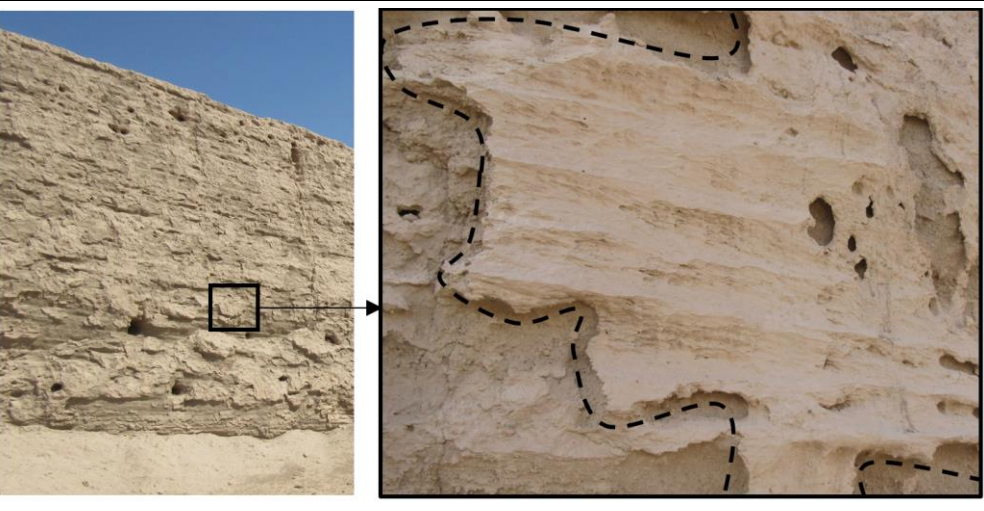
Turrets

The erosion of a once continuous wall into small stand-alone sections. The spacing of turrets is likely to be driven by construction process with erosion occurring at the joins between the wall sections.

Wall collapse

The failure of a wall or section of wall.

Atlas: earthen heritage deterioration processes and features

Deterioration Feature	Example on the historic walls at Suoyang
Crack	
Crust	

Flaking/
Scaling off



Fracture

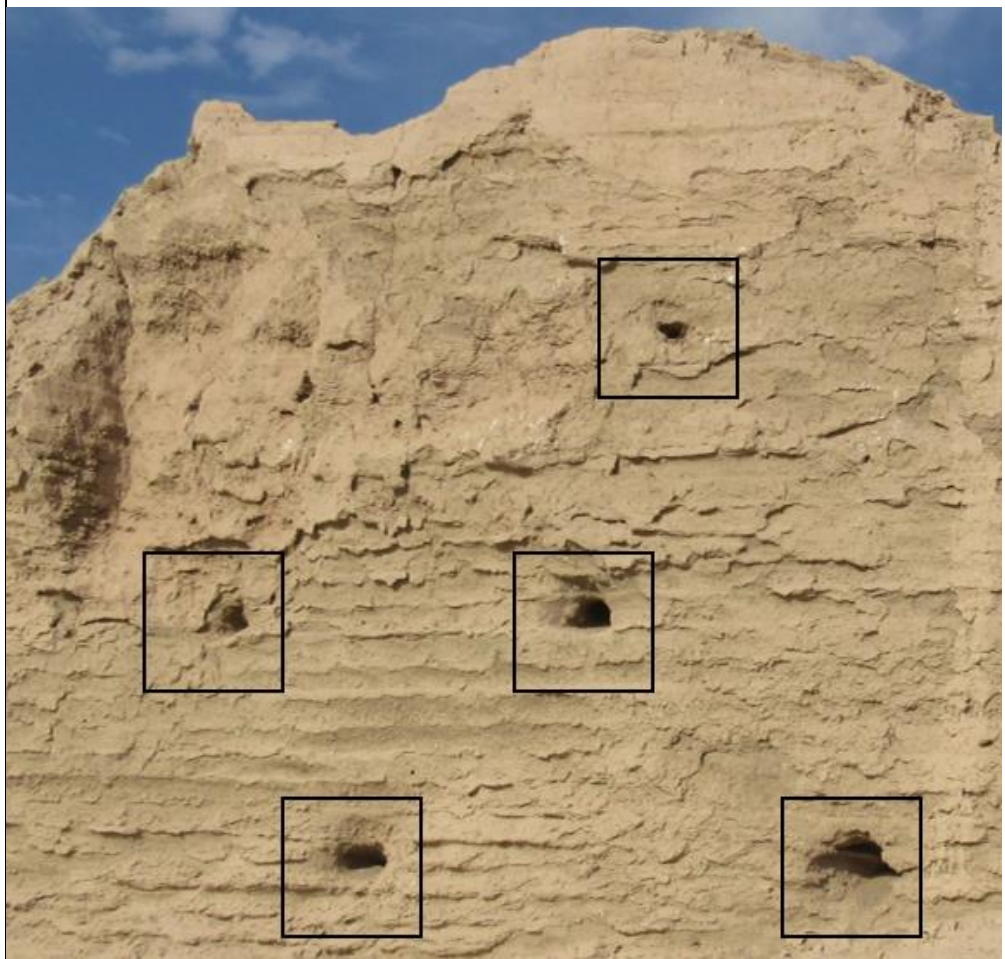


Photo credit: Dunhuang Academy

Gully

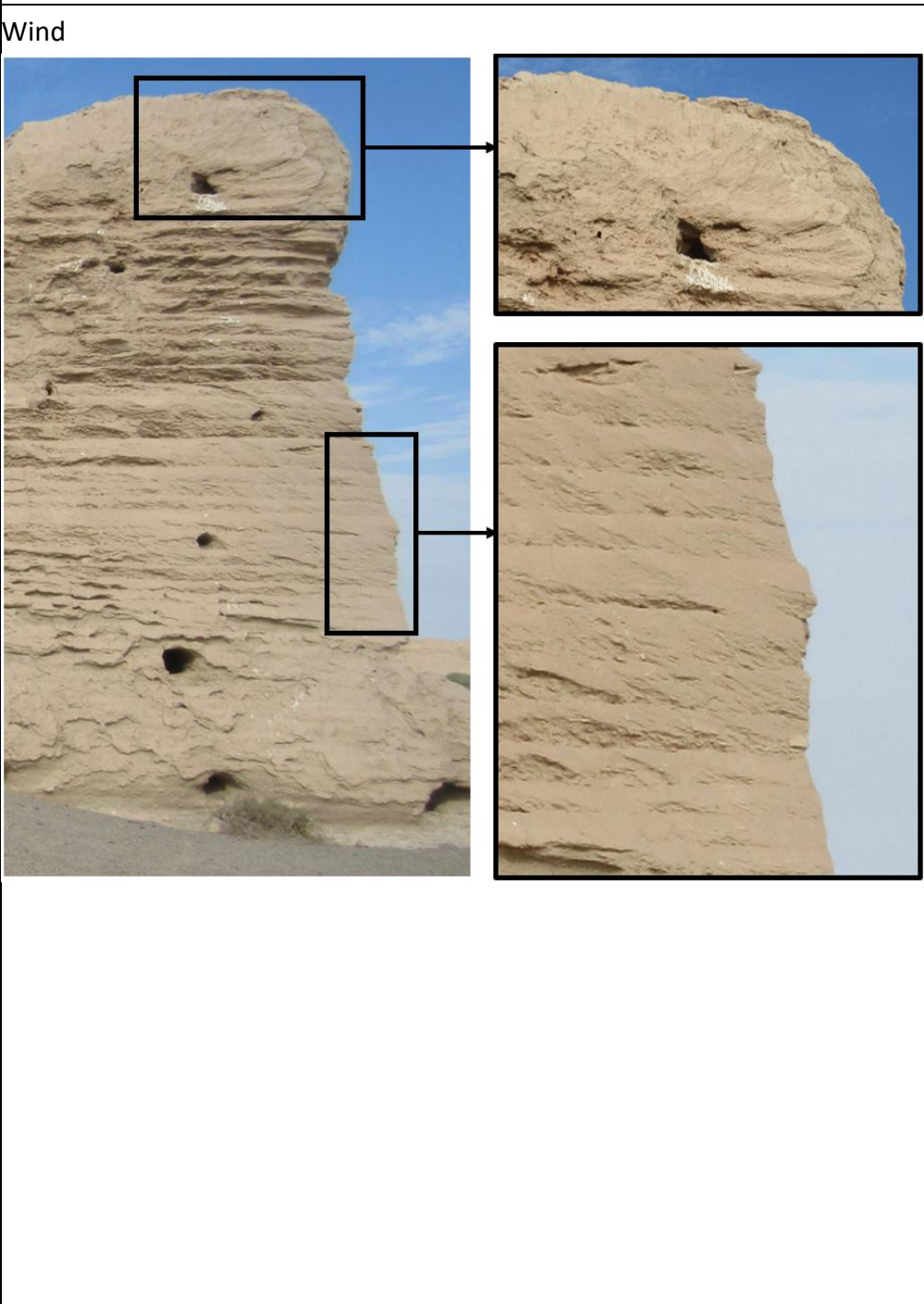


Hollow/Cavity

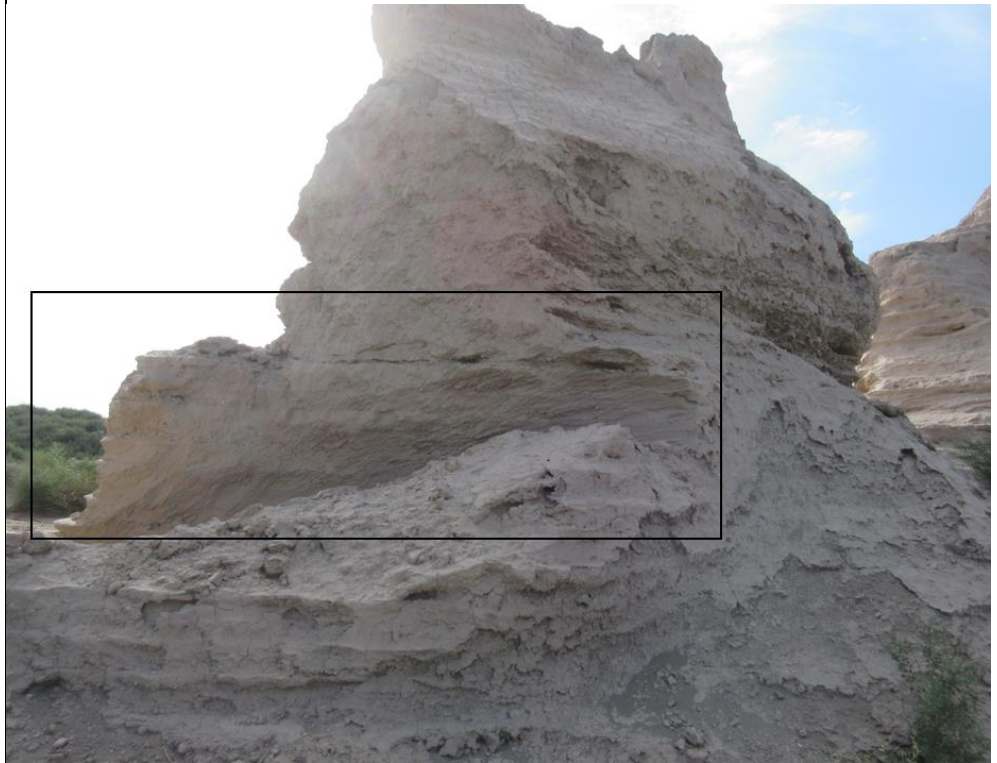


Outwash
slope



Pitting	
Polishing (wind and sand)	Wind 

Sand



Rounded
corners



Scouring at base	
Slump	 Photo credit: Dunhuang Academy

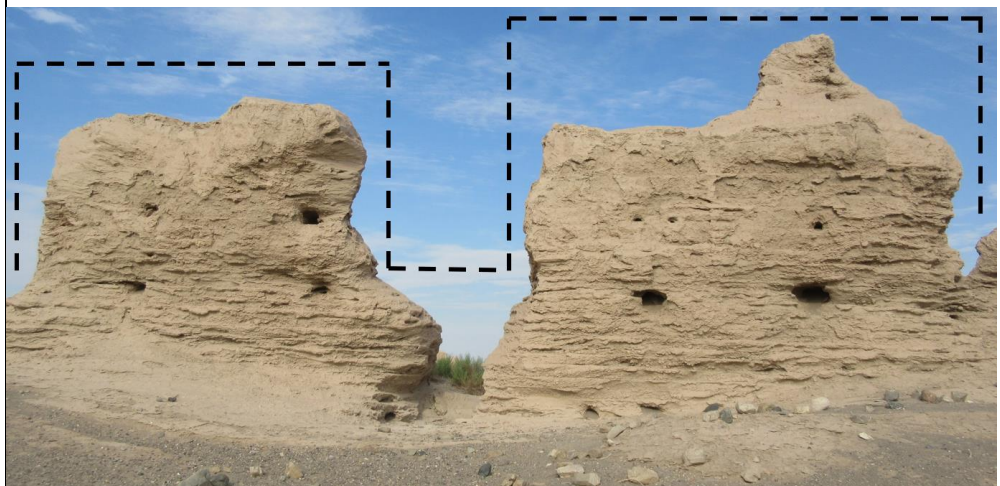
Slip



Slurry



Turrets



Wall collapse

