Assessment of 3D-printing of granular media for geotechnical applications

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Assessment of 3D-Printing of Granular Media for Geotechnical Applications

by

O. Adamidis¹, S. Alber¹ and I. Anastasopoulos¹

Abstract

The rapid evolution of 3D-printing has sparked interest for possible applications in geotechnical research. This paper investigates the use of 3D-printing to create an artificial granular medium that reproduces the morphological characteristics of a natural sand. Initially, individual particle geometries are captured from the reference sand using micro CT scanning. Subsequently, their capacity to represent the morphology of the original medium is assessed. An evaluation of 3D-printing options ensues, leading to the selection of PolyJet as the currently preferential technology. Post-printing, micro CT scanning reveals that only particles of diameter of 2 mm or larger can be reliably reproduced using PolyJet. Finally, 3D-printed media are assessed for their performance in possible geotechnical applications by examining their hydraulic conductivity using a constant head permeameter and their shear response using drained triaxial compression tests.

Keywords

Specimen Preparation, 3D-printing, CT scanning, Particle Morphology, Surrogate Soil, Hydraulic Conductivity, Triaxial Testing

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List of notation

C_{CK}	Empirical constant for Kozeny-Carman's formula of hydraulic conductivity
C_H	Empirical constant for Hazen's formula of hydraulic conductivity
d_{10}	particle size for which 10% of the material is finer
d_{50}	particle size for which 50% of the material is finer
d_L	Longest length of particle along principal axes in 2D
d_S	Shortest length of particle along principal axes in 2D
D_c	Degree of circularity
e	Voids ratio
E_{50}	Secant stiffness in triaxial compression, at 50% of maximum deviator stress
g	Acceleration of gravity
i	Hydraulic gradient
I_{AR}	Aspect ratio
I_{con}	Convexity
I_{el}	Elongation index
I_{fl}	Flatness index
I_r	2D Roundness index
I_{r3D}	3D Roundness index
I_{sph}	2D sphericity index
I_{sph3D}	3D sphericity index
I_{sol}	Solidity
k	Hydraulic conductivity
Re	Reynold's number
S	Ratio of surface to volume of a particle
$\bar{v}$	Average fluid velocity
η	Viscosity
ρ_w	Density of water
ϕ_{max}	Peak friction angle
ψ_{max}	Maximum dilation angle
DEM	Discrete Element Method
HPMC	Hydroxypropyl Methylcellulose
μCT	Micro Computed Tomography
PSD	Particle Size Distribution

1. Introduction

Additive manufacturing, or 3D-printing, is an area experiencing a rapid evolution, with new technologies and materials being introduced at an impressive rate. Recent advances in 3D-printing have stimulated interest into possible applications in the field of geotechnics. In particular, research is motivated by the unique opportunity offered by 3D-printing to create granular media with independent control of particle size, morphology, and material properties.

Promise lies in linking micro-scale particle characteristics to the macro-scale behaviour of granular media. For instance, Miskin and Jaeger (2013) examined the role of particle shape on packing stiffness. They altered the shape of particles using artificial evolution and used 3D-printing to recreate the computed shapes and verify the results of their simulations. Dal Ferro and Morari (2015) used 3D-printing to reproduce complex pore networks in an effort to gain insight into the effects of micro-heterogeneity on soil-water dynamics.

Another area of potential is the use of 3D-printing to recreate Discrete Element Method (DEM) generated particles and particle arrangements, offering a unique opportunity for meaningful validation. For example, Kondo et al. (2017) estimated the permeability of a granular medium through DEM simulations and validated their results by measuring the permeability of a 3D-printed specimen with identical particle arrangement.

Finally, Hanaor et al. (2016) recently proposed the use of 3D-printing to produce standardised geomaterials for quality control and calibration of geotechnical testing devices. This application is based on the ability of 3D-printing to consistently reproduce granular media with specific particle size, morphology, and material properties. Matsumura et al. (2017) further proposed 3D-printing of bonded granular specimens to eliminate the structural variation of granular assemblages.

Though there is potential in the use of 3D-printing for geotechnical research, important issues remain, mostly due to the novelty of such applications. This paper investigates the use

of 3D-printing to create artificial granular media that capture the morphology of a natural sand. The issues discussed include the selection of particle geometries so that the produced medium is representative of a natural sand, the selection of an appropriate 3D-printing technology, the assessment of the printed particles, and finally the assessment of the 3D-printed medium for its ability to capture the hydraulic conductivity and the shear response of a natural sand.

2. Particle Geometry Selection

2.1 Options

Three avenues exist for the definition of particle geometry when attempting to create a 3D-printed medium. The first is to design particles with simplified geometries (e.g. spheres) that do not represent natural sand grains but can be useful for validation of DEM simulations (e.g. Kondo et al. 2017). The second is to generate particles through stochastic algorithms that capture targeted morphology characteristics (Hanaor et al. 2016). The third is to obtain and reproduce the geometry of natural grains (e.g. Matsumura et al. 2017). The latter avenue is followed here, in order to assess the capability of 3D-printing to capture the morphological characteristics of a natural sand. This avenue also allows for direct comparison of shear response between the original and the 3D-printed medium. Hostun sand, widely used in geotechnical research, was selected as the reference material.

2.2 Acquiring the geometry of individual grains

In order to capture the 3D geometry of individual Hostun sand grains, micro computed tomography (μ CT) was employed. Micro CT is a non-destructive method that uses X-rays to visualise the 3D geometry of an object. It has been extensively used in the geotechnical field, to study the morphology of granular media and rocks (e.g. Desrues et al. 2006; Fonseca et al.

2012; Alshibli et al. 2015). Micro CT scanning was performed at the Institute for Biomechanics of ETH Zürich, using a μ CT scanner (μ CT50) of SCANCO Medical AG (Brüttisellen, Switzerland).

The choice of scanning resolution was made taking into account both the size of the grains, as well as the size of the smallest features that had to be captured. The approach suggested by Fonseca et al. (2012) was adopted: for Reigate Sand, which is characterised by irregular and complex shapes, they proposed a resolution of 5 μ m, which corresponds to $0.018d_{50}$. Extending this approach to Hostun sand, which is sub-angular to angular and for which $0.018d_{50} = 6 \mu\text{m}$, it was decided that a resolution of 5 μ m would be sufficient. Overall, 65 Hostun sand grains were μ CT-scanned, selected so that the number of grains from different diameter size intervals would correspond to the relevant mass fraction from a sieving analysis. An investigation regarding the number of grains required to represent the original medium is included in section 2.3.

The final geometries were obtained after image processing of the μ CT scans. The steps taken were image filtering, segmentation, and component labelling (Stauber and Müller 2008). Image filtering reduces noise and enhances the visualisation of features. During segmentation, the particles are identified by using a threshold value to discretise the images into two phases: objects and background. Finally, with component labelling all unconnected objects below a certain size, emerging due to noise or improper specimen preparation, are removed. Figure 1 depicts the 3D geometry obtained for some Hostun sand grains through μ CT scanning.

Figure 1. Examples of the 3D geometries obtained through μ CT scanning of Hostun sand grains

2.3 Comparison between proposed and reference media

In order to assess the number of grains required to produce an artificial medium that is representative of the original material, Particle Size Distribution (PSD) curves and morphology indices were used.

2.3.1 Definitions of morphology indices

While PSD curves can be obtained through standardised procedures, one has to choose which morphology indices to examine, from an array of numerous options that focus on features of different scales. Barrett (1980) established three independent properties to define morphology: form/shape, roundness, and texture/roughness. Particle shape corresponds to the broad, overall particle form (e.g. how elongated it is), roundness refers to the sharpness of corners and edges, and roughness refers to finer characteristics, too small to affect particle shape. Particle shape is quantified via aspect ratio, sphericity (indicating the degree of similarity to a sphere), and convexity (describing the compactness of a particle). Definitions of the relevant indices used here are given in Table 1. Roundness was originally evaluated via visual comparison to charts (e.g. Powers 1953) but numerical evaluations were used here (see Table 1). Finally, roughness was not considered in this study, since it is impossible for current

3D-printing techniques to recreate the fine, textural characteristics of natural sands. The implications of this limitation regarding the shear response of a 3D-printed medium are discussed in section 5.

Table1. Overview of morphology indices.

Author	Formula	Name	Definitions	Dimensions
SPHERICITY				
Alshibli et al. (2015)	$\frac{V_P}{V_S}$	I_{sph3D} : Sphericity Index	V_P : particle volume V_S : volume of sphere with diameter d_s (shortest particle diameter)	3D
Wadell (1932)	$\frac{2 \times \sqrt{\pi \times A}}{P}$	D_C : Degree of circularity	A: projected particle area P: particle perimeter	2D
Alshibli et al. (2015)	$\frac{A}{A_s}$	I_{sph} : Sphericity Index	A: projected particle area A_s : area of circle with diameter d_s	2D
ASPECT RATIO				
Fonseca et al. (2012)	$\frac{I}{L}$	I_{el} : Elongation index	I: intermediate particle axis L: longest particle axis	3D
Fonseca et al. (2012)	$\frac{S}{L}$	I_{fl} : Flatness index	S: shortest particle axis L: longest particle axis	3D
Cavaretta (2009)	$\frac{d_{Fmin}}{d_{Fmax}}$	I_{AR} : Aspect ratio	d_{Fmin} : minimum Feret diameter d_{Fmax} : maximum Feret diameter	2D
CONVEXITY				
Fonseca et al. (2012)	$\frac{V_P}{V_{CH}}$	I_{con} : Convexity	V_P : particle volume V_{CH} : volume of convex hull	3D
Cavaretta (2009)	$\frac{A}{A_c}$	I_{sol} : Solidity	A: projected particle area A_c : area of convex hull	2D
ROUNDNESS				
Alshibli et al. (2015)	$\frac{SA}{4 \times \pi \times \left(\frac{d_L + d_s + d_I}{6} \right)^2}$	I_{r3D} : Roundness Index	SA: particle surface area d_s : shortest particle diameter d_L : longest particle diameter d_I : intermediate particle diameter	3D
Alshibli et al. (2015)	$\frac{0.78 \times P}{\pi \times \left(\frac{d_L + d_s}{2} \right)}$	I_r : Roundness Index	P: particle perimeter d_s : shortest particle diameter d_L : longest particle diameter	2D

2.3.2 Morphology characteristics of Hostun sand

Before assessing whether a 3D-printed medium can represent Hostun sand, morphology indices for Hostun sand had to be calculated. Bowman et al. (2001), suggest that a specimen of 200 grain geometries in 2D is required to estimate the morphology characteristics of a sand. In order to depict a large number of Hostun sand grains in 2D, optical microscopy was employed here, with 570 grains examined. A Leica stereo microscope was used, provided by the Scientific Center for Optical and Electron Microscopy (ScopeM) of ETH Zurich. The captured images, at 7.14 μm resolution, were processed following the steps described for μCT scanning: image filtering, segmentation, and component labelling. An example of the binary images obtained is shown in figure 2. Subsequently, the particle area, the convex area, the perimeter, the centroid, as well as the shortest and longest diameters along the principal axes were calculated for each grain. The principal axes were obtained using principal component analysis, as proposed by Al-Raoush (2007). Furthermore, the smallest and largest Feret diameters were evaluated, corresponding to the smallest and largest distance between two parallel tangents to the particle. These calculations were then used to estimate morphology indices, reported in Table 2.

In figure 3, examples of sand grains are given that showcase variation for a range of morphology indices. While for shape indices variation can be easily interpreted, roundness is more challenging. A roundness index equal to one corresponds to a smooth particle, whose shape is not far from a sphere. Higher values correspond to more angular particles. However, lower values can also be calculated if the average diameter of a particle is large compared to its perimeter. In general, as depicted in figure 3, the roundness index of Alshibli et al. (2015) captures the presence of large features, rather than the sharpness of particle corners.

Figure 2. Example of microscopy image: (a) before; and (b) after binarisation

Table 2. Morphology indices for Hostun sand.

	d_s (μm)	d_L (μm)	I_{sph}	D_c	I_{AR}	I_{sol}	I_r
Min.	100	136	0.629	0.789	0.362	0.863	0.907
Max.	692	892	2.282	1.035	0.917	0.990	1.177
Mean	391	498	1.144	0.927	0.686	0.964	1.001
SD	106	132	0.252	0.041	0.110	0.019	0.042

2.3.3 Assessment of proposed medium

In order to assess whether the proposed medium was representative of Hostun sand, PSD curves and histograms of morphology indices were used. Three media were examined, one containing 25 individual particle geometries, one 45, and one 65. In all media, the number of grains from different diameter size intervals corresponded to the relevant mass fraction from sieving analysis of Hostun sand. This simplifying approach neglects the fact that larger grains are heavier and results in a slight over-representation of larger grains, whose effects are discussed below.

Figure 3. Examples of morphology indices variation, including where appropriate the circles taken into account for calculations: (A) Sphericity Index; (B) Degree of circularity; (C) Aspect Ratio; (D) Solidity Index; and (E) Roundness Index

The produced PSD curves presented in figure 4 were adequately close to each other. The dashed lines of figure 4 correspond to Hostun sand. One was obtained through sieving while the other was calculated using microscopy results. For the latter, the diameter depicted is the minimum Feret diameter multiplied by 0.91, as suggested by Altuhafi et al. (2013), in order to account for particles passing through sieve openings with their principal axes non-parallel to the sieve's grid. The ordinate of this curve was calculated using 2D particle area. Despite this simplification, the two curves match remarkably well, giving confidence in the use

of 2D particle depictions for the computation of PSD curves. The same approach was used to calculate the PSD curves corresponding to the three proposed media, using 2D projections of the μ CT scans, with the plane of projection perpendicular to the shortest axis of each particle, as suggested by Cavaretta (2009) for particles laying on a flat surface. Despite the slight overrepresentation of larger particles caused due to the selection process of the grains scanned, the PSD curves for the proposed media remain close to those for Hostun sand.

Figure 4. Comparison of Particle Size Distribution (PSD) curves

Table 3. Morphology indices for the proposed artificial medium, with 65 grain geometries.

	d_s (μm)	d_L (μm)	I_{sph}	D_c	I_{AR}	I_{sol}	I_r
Min.	260	300	0.824	0.781	0.500	0.885	0.970
Max.	650	830	1.726	0.956	0.881	0.979	1.124
Mean	420	535	1.145	0.878	0.724	0.945	1.069
SD	91	127	0.207	0.040	0.093	0.020	0.048

In order to meaningfully compare the morphology characteristics of the proposed media to those of Hostun sand, calculated in 2D, the same projections of μ CT scans used for PSD curves were employed. Figure 5 presents the histograms of morphology indices for the

reference and the proposed media. The inclusion of a larger number of individual geometries expectedly leads to media with better distributed histograms. Significant decreases in spikes for the histograms of most properties are observed when increasing the number of individual geometries from 25 to 45. Further increase from 45 to 65 geometries reduces spikes to a lesser extent. At 65 individual grain geometries, the morphological characteristics of the proposed medium (table 3) capture reasonably well those of Hostun sand (table 2). Garboczi et al. (2017), studying crushed waste glass, showed that 50 3D particles are enough to capture mean morphology indices but suggest that 300 are required to accurately capture distributions. Here, the comparison of morphology indices for the reference sand and the proposed artificial medium is favourable in terms of both mean value and standard deviation, suggesting less distribution in particle shape indices compared to crushed glass. Very good accordance is achieved in terms of sphericity index (I_{sph}), solidity index (I_{sol}) and aspect ratio (I_{AR}). Figure 5 also shows good agreement for the histograms of area, perimeter, and convex hull area. A slight deviation is observed in terms of degree of circularity (D_C), and particle roundness (I_r). These deviations, which are small in value, are due to the slight over-representation of larger particles discussed above, which tend to be more elongated and more irregular than smaller ones. Even if the medium containing 45 individual grain geometries could be considered sufficiently representative of Hostun sand, the medium with 65 grain geometries was used for 3D-printing, thanks to the enhanced representation of Hostun sand morphology it offered.

Figure 5. Comparison of histograms of morphology indices between microscopy results and 2D projections of μ CT scans: (A) Sphericity Index; (B) Degree of circularity ; (C) Aspect Ratio; (D) Solidity Index; (E) Roundness Index; (F) Area; (G) Perimeter; and (H) Convex Hull area

3. 3D-Printing

3.1 Options

The potential 3D-printing technologies investigated, summarized in table 4, were those available within ETH Zurich. The principal parameters considered included resolution, available materials, existence of support material, time, and cost. To begin with, resolution had to be adequate to reproduce important features that affect the shape and roundness of grains. As

already stated, none of the technologies examined could recreate textural features. Secondly, the material used for the grains should be as close as possible to quartz, of which Hostun sand is made. In reality, this was impossible to realise as most materials available for 3D-printing are significantly softer than quartz. Thirdly, the existence of support structures that had to be manually removed was considered prohibitive for the size and number of grains required for geotechnical applications. Finally, the printing process had to be quick and affordable as thousands of grains are required for a typical soil specimen.

Table 4. Overview of investigated 3D printing technologies.

Technique		Material	Resolution	Support removal	Time and Cost
Stereolithography (SLA)		Photopolymer	~ 25 μm (z) ~ 140 μm (x/y)	Manual removal	Quick, Affordable
PolyJet		Photopolymer	~ 16 μm (z) ~ 40 μm (x/y)	Solution bath	Quick, Affordable
Selective Sintering (SLS)	Laser	Metal, ceramic, powder	~ 50-150 μm (z) ~ 200-300 μm (x/y)	No support	Material-dependent
Selective Melting (SLM)	Laser	Metal powder	~ 50 – 100 μm	No support	Quick, Expensive
Nanoscribe Professional GT	Photonic	Photopolymer	< 1 μm	-	Slow, Expensive

After comparing the technologies listed in table 4, it was concluded that PolyJet is preferential for the quantity of small and highly detailed particles required. It is on the high end of the examined technologies regarding resolution, and it provides an avenue for non-manual support material removal using a caustic solution bath. Moreover, PolyJet is quick and affordable and can thus be used to efficiently produce thousands of grains.

Despite the advantages of PolyJet, certain drawbacks exist. Firstly, the resolution of 40 μm is insufficient for printing the scanned particles in real scale with adequate detail. Thus, scaling up was necessary, with three scaling factors chosen: 4, 8, and 16. The mean diameter of

the particles at scaling factors 4, 8, and 16 was 1.7 mm, 3.4 mm, and 6.7 mm respectively. At the lowest scaling factor considered, the shortest dimension of the smallest grain corresponded to about 20 voxels; anything below that was considered inadequate. Secondly, the available materials for PolyJet are photopolymers and are thus much softer than quartz. While larger and softer than Hostun sand grains, these particles can still be useful for the possible geotechnical applications outlined in the introduction. Indeed, in the handful of cases reported in literature where 3D-printed geomaterials were examined, PolyJet or equivalent UV-hardening polymer technology was also used (Miskin and Jaeger 2013; Hanaor et al. 2016; Dal Ferro and Morari 2015; Matsumura et al. 2017). Considering the resolution of most currently commercially available 3D-printing technologies, the level of detail captured by our μ CT scans could be reduced to a level closer to the voxel of the selected 3D-printing technology, without affecting the produced grains.

Powder-based technologies could be an interesting alternative, thanks to the lack of support structures and the variety of available materials for printing, which can offer higher material stiffness compared to PolyJet photopolymers. Nevertheless, for the technologies considered here, a scaling factor of at least 20 would be required for the limitation of 20 voxels along the shortest particle dimension to be satisfied. While such scaling was considered excessive in this study, future improvements in resolution could render powder-based technologies preferable to PolyJet.

3.2 Printing process

Printing was performed at the Department of Mechanical and Process Engineering of ETH Zurich, using a PolyJet Objet500 Connex3 (Stratasys) printer. A printing resolution of 30 μ m along the z axis and 40 μ m along the x and y axes was used. Depending on the scaling factor, the set of 65 grain geometries was printed adequate times to fill a triaxial specimen of 50 mm in diameter and 100 mm in height. The high temperature resistant material RGD525 (Stratasys,

2018) was selected, because it had the highest modulus of elasticity (3.2 to 3.5 GPa) among the available materials for Polyjet. The support structures were created using the soluble support material SUP706, which was removed by submerging the prints in an aqueous solution bath containing 2% NaOH and 1% NaSiO₃. The solution was subsequently neutralised using vinegar and washed away under water flow. Figure 6 depicts some instants from the printing process.

Figure 6. Polyjet 3D-printing process: (a) printing platform of PolyJet Objet500 Connex3; (b) printed particles of scale factor 16 before support material removal; (c) printed particles of scale factor 4 before support material removal; (d) solution bath for removal of support material; (e) manual removal of support material under waterflow; and (f) produced grains for the three scaling factors

3.3 Assessment of printing quality

Even if often skipped in similar studies, quality assessment of the printed grains was deemed necessary since PolyJet 3D-printing is developed and typically used for larger objects,

where the reproduction of small features is not as important. To this end, μ CT scans of printed particles were performed and compared to the ideal geometries. For each scale factor, 10 randomly selected printed particles were scanned. Since the printed particles were larger than the original, the scanning resolution was modified accordingly. For the particles of scale factors 16, 8, and 4, scanning resolutions of 48.4 μ m, 34.4 μ m, and 20 μ m were used, respectively. Scanning was performed at the Institute for Biomechanics of ETH Zurich. Following μ CT scanning, geometrical properties and morphology indices were calculated for each particle. They were then compared to those of the appropriately scaled equivalent original particle of sand. The mean value and standard deviation of differences for the properties considered are summarized in table 5.

Table 5. Differences of geometrical properties and morphology indices between 3D-printed and original particles.

	scale 4		scale 8		scale 16		scale 4 new	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean								
diameter	-10%	6%	-6%	2%	-3%	1%	-3%	3%
Area	9%	10%	-9%	2%	-7%	1%	19%	8%
Volume	-28%	18%	-17%	4%	-9%	3%	-10%	5%
I_{sph3D}	-7%	14%	-6%	9%	0%	1%	1%	25%
I_{el}	-2%	7%	-2%	4%	0%	4%	0%	5%
I_{fl}	0%	8%	3%	5%	0%	1%	1%	13%
I_{con}	10%	9%	1%	2%	2%	2%	4%	3%
I_{r3D}	34%	12%	3%	3%	0%	1%	25%	8%

The potential of 3D-printed grains to reliably reproduce the targeted geometries was found to vary with size. Mean diameter and volume were consistently lower than expected, with deviations increasing as the scaling factor decreased. At worse, for scaling factor 4, volume was on average almost 30% lower than required. Morphology indices did not deviate as much, even for the scaling factor of 4. This means that the printed particles adequately reproduced the shape of the targeted geometries, as expressed by sphericity (I_{sph3D}), elongation (I_{el}), flatness (I_{fl}), and convexity (I_{con}), even if the volume of the particles was lower than targeted. The grains of scaling factors 8 and 16 reproduced the targeted geometries with sufficient reliability, adequately capturing all morphology indices, including roundness, which refers to smaller features. However, roundness (I_r) deviated by about 30% for the scaling factor of 4. Considering the size of these grains, the printing resolution could not be responsible for such deviation in roundness or in volume. Instead, the process of support material removal was culpable: the caustic solution typically used to dissolve the support material was found to also attack the particles, corroding their outer layers. This explains the larger deviations in diameter and volume for smaller grains. Figure 7 visually confirms this finding by comparing the μ CT scan of the same grain geometry, printed in all scales. Corrosion along the printed layers also explains the increase in surface area for the scaling factor of 4. Although this effect is unimportant and hence neglected for typical Polyjet printing applications, it becomes crucial for the small particles examined here.

After this observation, new grains were printed for the scaling factor of 4 and the typical process for support material removal was altered. Initially, the prints were broken up manually under water flow. Subsequently, they were exposed to the caustic solution for 45 minutes only, as opposed to the few hours which are commonly applied. Finally, after neutralisation of the caustic solution, the remaining support material was removed under water flow. As seen in table 5 and figure 7, the produced particles better represented the targeted geometries. Nevertheless, they still did not adequately capture the roundness index. The increase in

surface area despite the reduction in volume shows that despite the laborious process followed, not all support material was removed. Nevertheless, longer exposure to the caustic solution was not pursued as it would further reduce volume.

It can be concluded that the process of support material removal imposes an additional, unexpected limitation for the use of PolyJet 3D-printing. It is suggested that a mean particle diameter of 2 mm, here corresponding to the smallest particle of scaling factor 8, is used as a minimum for PolyJet 3D-printing. This finding highlights the need for quality control of 3D-printed granular media, at least until sufficient experience is accumulated to guarantee the reliability of the used printing technique.

Figure 7. Comparison of an original grain with particles printed at different scales

4. Hydraulic Conductivity

As previously stated, 3D-printing could be used to elucidate how micro-scale characteristics affect macro-scale behaviour. To showcase such an application, the hydraulic conductivity of the three available 3D-printed media is measured and then compared to commonly used formulas, in order to experimentally confirm the square law hypothesis of how particle size affects hydraulic conductivity. This is possible because the 3D-printed media share the same coefficient of uniformity, the same packing, and practically the same morphological

characteristics, while having different grain sizes; a feat impossible to achieve with natural granular media.

4.1 Constant head permeameter

Hydraulic conductivity was measured using the constant head setup of **Fig. 8**, broadly following ASTM D2434-68. The differences to the ASTM standard included a fluid flow from the bottom to the top of the specimen and the use of a custom-built permeameter. More specifically, the experimental setup consisted of a constant head tank, filled continuously with de-aired fluid and connected to the bottom of the permeameter. The permeameter cylinder had a mean inner diameter of 40.43 mm. Perforated plates were installed at both ends of the permeameter, whose coarseness increased with the particle size of the medium. Manometer tubes were connected to two points of the permeameter, with vertical distance of 49.7 mm. A weight applied a stress of 4 kPa to the specimen, to keep specimen volume constant during saturation and testing. An outlet tube at the top of the device channelled fluid to a balance connected to a computer, which took measurements of weight at regular time intervals. Fluid temperature was recorded for each measurement. The specimens were prepared by dry pluviation and tapping when necessary. All specimens had a voids ratio of $e = 0.835 \pm 0.010$. To enhance saturation, three cycles of vacuum and CO₂ were applied before allowing fluid to enter the permeameter.

Figure 8. Laboratory setup for hydraulic conductivity measurements

Measurements were performed using both de-aired water and a de-aired hydroxypropyl methylcellulose (HPMC) aqueous solution, prepared according to Adamidis and Madabhushi (2015). The viscosity of the HPMC solution was 37.7 mPa·s at 19.8 °C, measured with a Lamy Rheology B One Touch viscometer at different shear rates. The viscous fluid was used to achieve laminar flow conditions for the coarse 3D-printed media. According to Wood (2009), the transition from laminar to turbulent flow occurs for values of Reynold's number Re between 1 and 10. Taking the Reynold's number for the transition from laminar to turbulent flow, a critical velocity $\bar{v}_{crit}$ can be calculated, if d_{50} is the diameter for which half of the soil particles by weight are finer, ρ_w is the density of the fluid, and η is the viscosity of the fluid:

$$\bar{v}_{crit} = \frac{Re \cdot \eta}{\rho_w \cdot d_{50}} \quad (1)$$

For Hostun sand, $d_{50} = 0.341 \text{ mm}$. Taking the upper threshold of Reynold's number $Re = 10$, the maximum allowable velocity with water is 30 mm/s for Hostun sand, 7 mm/s for scaling factor 4, 4 mm/s for scaling factor 8, and 2 mm/s for scaling factor 16. While these velocities are reasonable for Hostun sand and even for scaling factor 4, they could not be achieved for the other media using water. With the HPMC solution, critical velocities were multiplied by viscosity and thus became sufficiently high for the measurements to be reliable.

355

356 **4.2 Hydraulic conductivity results**

357 The rate of fluid discharge ($\Delta V/\Delta t$) was calculated from weight and time measurements. This
358 rate was constant throughout each measurement. Using the area A of the specimen and the
359 head difference ΔH of the manometer tubes placed at distance L , hydraulic conductivity k
360 (m/s) was calculated as follows:

$$361 \quad k = \frac{\bar{v}}{i} = \frac{\frac{1}{A} \frac{\Delta V}{\Delta t}}{\Delta H/L} \quad (2)$$

362 This coefficient was converted to hydraulic conductivity for water at 20°C, by multiplying it by
363 the ratio of viscosity of the used fluid at test temperature to viscosity of water at 20°C. The
364 results of the measurements are presented in figure 9. A linear relation between the hydraulic
365 gradient and the flow velocity was realised for Hostun sand and for scaling factor 4 using
366 water, as one would expect considering critical velocities. For the other two media, a linear
367 relation was captured using the viscous HPMC solution.

368

369 **4.3 Comparison to hydraulic conductivity formulas**

370 The most commonly used formulas for hydraulic conductivity are those of Hazen (1892),
371 Kozeny (1927), and Carman (1956). According to the formula of Hazen, hydraulic conductivity k
372 (cm/s) is a function of the characteristic diameter d_{10} (cm) as follows:

$$373 \quad k = C_H \cdot d_{10}^2 \quad (3)$$

374 where C_H is an empirical constant, typically assumed equal to 100. In fact, the value of C_H can
375 vary dramatically, ranging from 1 up to 1000 in different textbooks (Carrier 2003). Despite the
376 large range of C_H , the use of Hazen's formula remains widespread thanks to its simplicity. The
377 formula proposed by Kozeny (1927) and modified by Carman (1956) is as follows:

$$378 \quad k = \frac{\rho_w \cdot g}{\eta} \cdot \frac{1}{C_{CK}} \cdot \frac{1}{S^2} \cdot \frac{e^3}{1+e} \quad (4)$$

379 where: ρ_w is the density of the fluid, g is the acceleration of gravity, η is the viscosity of the

fluid, e is the voids ratio, S is the ratio of surface to volume for the soil particles, and C_{CK} is an empirical constant, typically taken as $C_{CK} \approx 5$ (Carrier 2003).

In Hazen's formula, the hydraulic conductivity is proportional to the square of a measure of particle size (d_{10}). This is also true for the Kozeny–Carman formula, where the reciprocal of S has dimensions of length. This square law is consistent with Poiseuille's formula for laminar flow in a narrow tube, where the average fluid velocity $\bar{v}$ is expressed as a function of the square of the tube's radius r_0 :

$$\bar{v} = \frac{\rho_w \cdot g \cdot r_0^2}{8 \cdot \eta} \cdot i \quad (5)$$

The comparison of measured results to those of hydraulic conductivity formulas is presented in figure 10. For Hazen's formula, the coefficient C_H was chosen to match the calculated hydraulic conductivity of Hostun sand. For the equation of Kozeny-Carman the coefficient C_{CK} was given its typical value of 5 (Carrier 2003), while S was calculated using the 3D image analysis of the μ CT scans of Hostun sand grains. All relevant values for these calculations are summarized in table 6. It is worth pointing out how well Kozeny-Carman's formula performed in predicting hydraulic conductivity. The results of figure 10 confirm the square law linking hydraulic conductivity to particle size. The small deviation for the scaling factor 4 medium is attributed to the previously discussed incomplete removal of support material, which increased surface area and led to a larger S parameter in Kozeny-Carman's formula.

Table 6. Parameters used for the calculation of formulas for hydraulic conductivity.

d_{10} [mm]	C_H	C_{CK}	e	S [1/mm]
0.25	220	5	0.836	24.62

Figure 9. Hydraulic conductivity measurements. The velocities presented here are those measured, multiplied by the ratio of fluid viscosity at test temperature over water viscosity at 20°C

Figure 10. Measured hydraulic conductivity in function of scaling factor and comparison to the predictions of the formulas of Hazen and Kozeny-Carman

5. Shear Response

In this section the shear response of the 3D-printed media is compared to that of the reference sand. In the past, 3D-printed media have been shown to capture the very fundamentals of soil response (Hanaor et al. 2016). Here, direct comparison with Hostun sand, which the 3D-printed media aim to emulate, allows for an increased level of scrutiny in result interpretation.

5.1 Drained Triaxial Compression tests

The 3D-printed grains of scaling factors 4, 8 and 16 were subjected to drained triaxial compression tests. The tests were performed using the triaxial devices of the Institute for Geotechnical Engineering (IGT) of ETH Zurich (Arenson and Springman 2005). Specimens of 50 mm in diameter and 100 mm in height were prepared by wet pluviation in de-aired water. Densification was achieved by tapping. For all tests of 3D-printed media, the effective confining stress was kept at 10 kPa so that the dimensionless ratio of confining stress to stiffness of grain material could correspond to that of natural sand, as suggested by Hanaor et al. (2016). Considering a modulus of elasticity of 90 GPa for quartz (Hostun sand) and 3.3 GPa for the RGD525 material of the 3D-printed grains, a confining stress of 270 kPa for Hostun sand corresponds to 10 kPa for the 3D-printed grains. The specimen size was kept the same, even as the grain size increased, in order to assess the potential of using scaled-up 3D-printed geomaterials for the calibration of typical geotechnical devices. The testing procedure followed ASTM D7181–11. Full barrelling was assumed for the specimens, as was confirmed by visual observation. The test for scaling factor 16 was repeated to assess whether the 3D-printed media can be reused for triaxial testing. Results are presented in figure 11, which also includes results for Hostun sand tested at 270 kPa of initial confinement. In order to assess the performance of maintaining the same dimensionless ratio of confining stress to stiffness of grains for the natural and the 3D printed media, the results of another drained compression

for Hostun sand are presented, at 10 kPa of initial confinement, the same as that for the 3D-printed media. Initial testing of the medium of scaling factor 4 produced a response that was softer than anticipated, due to the incomplete removal of support material. Extensive further support material removal was manually undertaken under water flow, before testing this medium again. The results of this test are included in figure 11.

Figure 11. Comparison of shear response between the 3D-printed media and Hostun sand. Drained triaxial compression test results: (A) stress ratio; and (B) volumetric response

The 3D-printed media captured certain aspects of Hostun sand's shear response. For all 3D-printed media, the stress ratio q/p' increased to a peak before reducing towards the critical state. The peak was observed at much larger strains for the 3D-printed media than for Hostun sand. The peak friction angles captured were similar to that for Hostun sand at $\sigma'_3 = 270 \text{ kPa}$ and significantly lower than that for Hostun sand at $\sigma'_3 = 10 \text{ kPa}$ (table 7). In terms of volumetric response, the 3D-printed media exhibited a more pronounced initial contractive phase than Hostun sand but did eventually dilate as expected. This increased initial contraction was likely due to the softer material of the grains, since particle shapes and packing were not that different from the specimens of Hostun sand. The maximum dilation angle of Hostun sand at $\sigma'_3 = 270 \text{ kPa}$, computed according to Schanz and Vermeer (1996), was close to that of the three 3D-printed media (table 7). In contrast, Hostun sand at $\sigma'_3 = 10 \text{ kPa}$ was much more dilative. Maintaining the same ratio of confining stress to stiffness of grain material for the 3D-printed media as for Hostun sand produced good agreement in terms of maximum friction and dilation angle, as opposed to using the same level of confinement. It is hypothesised that peak friction and dilation angles were captured by the 3D-printed media thanks to reliable reproduction of particle shape, roundness, and packing; which in turn led to recreation of grain interlocking, while maintaining the ratio of confinement to grain stiffness constant.

Despite capturing the maximum friction and dilation angle, the shear response of Hostun sand was not fully recreated. Stiffness was much lower for the 3D-printed media than for Hostun sand. Considering similar particle shapes and packing, this difference was likely due to the stiffness of the PolyJet printed grains being much lower than that of quartz, of which Hostun sand consists, and was possibly affected by the inability of 3D-printing to reproduce the textural features that define roughness. Using the same ratio of confinement to grain stiffness was not enough to recreate the stiffness of the reference sand. The scaling factor was also of importance: an increase in scaling factor led to an increase in medium stiffness, particularly for the medium of scale 16. Another aspect of response affected by specimen size

was the emergence of a “wavy” pattern in the curves of figure 11, which was exacerbated as the scaling factor increased. Bernhardt et al. (2016) describe how the coarser network of force chains formed for larger particles is more severely affected by the collapse of individual chains, leading to a “wavy” pattern. Similar effects are evident in the results of Hanaor et al. (2016), who used specimens of 38 mm x 76 mm, containing particles of mean diameter 2 mm, as well as in the results of Matsumura et al. (2017), who used specimens of 50 mm x 100 mm, containing particles of diameter from 4.76 mm to 9.5 mm. This “wavy” pattern was attributed to the soft material by Hanaor et al. (2016) but particle size seems to be the decisive parameter. Indeed, for the scaling factor of 16 for which this “wavy” pattern emerged, some of the particles had a diameter greater than 1/6 of the specimen diameter, suggested by ASTM D7181-11 as a maximum. For the scaling factors of 4 and 8, which did not violate the requirements of ASTM D7181-11, this pattern was not as prominent. To verify this conclusion, another triaxial test was performed for scaling factor 16, in a specimen of diameter 75 mm and height 150 mm, which did not violate the requirements of ASTM D7181-11 and is labelled “large” in figure 11. Indeed, the “wavy” pattern was significantly reduced for the larger specimen. Other parameters such as peak friction angle and peak dilation angle were not altered.

Table 7. Properties calculated from drained triaxial compression tests.

medium	e	$\varphi_{\max}$ [°]	$\psi_{\max}$ [°]
Hostun, $\sigma'_3 = 270$ kPa	0.737	38.9	10.1
Hostun, $\sigma'_3 = 10$ kPa	0.731	45.5	17.7
3Dp, scale 4	0.777	39.7	9.0
3Dp, scale 8	0.702	38.7	9.3
3Dp, scale 16	0.672	39.8	9.5

5.2 Reuse of particles

For some applications, such as the calibration of geotechnical devices, reuse of 3D-printed media would be advantageous. In order to assess how much such a 3D-printed medium is affected by a compression test and whether it can be reused, the triaxial test for the medium of scaling factor 16 was repeated. The medium with the largest grains was chosen, as stress concentrations there would be higher, leading to more significant distortions of the grains. However, as seen from the results of figure 11, no significant change in response was recorded.

Post-testing, 10 particles from the specimens of scaling factor 8 and 16 were randomly selected and subjected to μ CT scanning, to reveal potential changes in their morphology. Scanning resolutions of 48.4 μ m and 34.4 μ m were chosen for the scaling factors of 16 and 8 respectively. Morphology indices were compared to those of the equivalent original particle of sand. Mean values of differences are shown in table 8, which can be compared to those of table 5, obtained before testing. Slightly larger changes were observed for scaling factor 16, likely due to more severe localised loading. However, overall alterations in morphology were not significant. These results, in tandem with the repeat test for scaling factor 16 signify that the reuse of 3D-printed media in triaxial testing is possible.

Table 8. Differences of morphology indices between 3D-printed and original particles, after triaxial tests.

	scale 8		scale 16	
	Mean	SD	Mean	SD
I_{sph3D}	7%	10%	1%	6%
I_{el}	-2%	4%	-2%	1%
I_{fl}	0%	3%	2%	2%
I_{con}	4%	2%	4%	2%
I_{r3D}	4%	4%	1%	2%

6. Conclusions

The rapid evolution of 3D-printing has sparked interest regarding potential applications in geotechnics. This paper examines the use of 3D-printing as a method for the creation of granular media of geotechnical interest. Hostun sand was selected as a reference material to be recreated, in order to allow for meaningful comparisons between the 3D-printed and the reference media, regarding morphology characteristics, hydraulic conductivity, and shear response. Initially, 65 individual grain geometries were captured using micro CT scanning. These were shown to adequately reproduce the PSD curve of Hostun sand and to sufficiently represent morphological characteristics related to particle shape and roundness. Particle roughness could not be captured with any of the 3D-printing techniques considered. After an investigation of 3D-printing technologies, PolyJet was found to offer the best combination of resolution, cost, and speed while allowing for non-manual support material removal. Nevertheless, the available resolution still necessitated scaling up of the original grains in order to adequately reproduce important morphological features. Three scaling factors were used when 3D-printing the captured geometries: 4, 8, and 16. Post-printing, micro CT scanning revealed that the typical process used for support material removal, using a bath of caustic solution, also affects the grain material. Due to this effect, only particles of diameter of 2 mm or larger could be reliably generated; corresponding to the media of scaling factors 8 and 16. The produced 3D-printed media were then subjected to constant head permeability tests, through which the square law between hydraulic conductivity and particle size was confirmed. This application was possible because 3D-printing allowed the decoupling of particle morphology from particle size. Finally, the shear response of the 3D-printed media was examined using drained triaxial compression tests. The printed media managed to capture well the aspects of shear response that are related to interlocking, reproducing the peak friction and dilation angle of a Hostun sand specimen, as long as the ratio of confining stress to grain

stiffness was kept constant. On the other hand, the medium stiffness was not well captured, likely due to the low stiffness of the material used for the 3D-printed grains, as well as due to the inability of 3D-printing to recreate textural features.

This study informs the process of creating 3D-printed granular media for an array of geotechnical applications. For micro to macro scale investigations, applications where particle roughness is important should be avoided as this aspect of morphology cannot be reproduced with 3D-printing. In applications where material stiffness is crucial, SLS or SLM 3D-printing should be considered as potentially preferential to PolyJet, thanks to the availability of much stiffer materials, even if they underperform in terms of resolution. In applications where particle shape, roundness and packing are of interest, PolyJet 3D-printing performs well, as shown with this study's hydraulic conductivity investigation. Moreover, the hydraulic conductivity and the shear response results presented here bode well for the creation of experimental setups for Discrete Element Method (DEM) validation. For such applications, even the low medium stiffness captured in triaxial experiments needs not be a problem since the hypothesised culprits, particle stiffness and roughness, can be appropriately taken into account in DEM simulations. Finally, the use of 3D-printed media for calibration of typical geotechnical devices remains possible, since such media were shown to capture major aspects of natural soil response while offering the possibility for reuse. However, attention is required regarding particle size effects, especially considering the resolution offered by most commercially available 3D-printing technologies.

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