The symmetric analysis does not have a significant hogging section and as such does not allow the hogging capabilities of the equivalent masonry beams to be fully tested. The results of the SMB runs with masonry beams do not show a significant difference from the results of the SEB runs with the elastic beams. It can be seen, however, that the parameters f_b and κ_{crit} do have an impact on the response of the EMBs. In particular, a value of κ_{crit}=1.0×10^{-6} may be too small. The oblique analyses described in the following section will allow a fuller comparison of the response of the EMBs and the masonry facades in hogging.

8.3 Oblique analysis

8.3.1 Description of analysis

The second example problem consists of a tunnel of the same diameter and depth as the symmetric problem under the same masonry building, but with the building aligned such that it is eccentric and oblique to the tunnel centre line. The layout of the problem is shown in figure 8.25. The geometry of this problem is similar to the oblique example used in previous work by Augarde (1997), Liu (1997) and Burd et al. (2000). Four different finite element analysis run types are undertaken with the oblique problem as summarised in table 8.8: the first (OGF) is a greenfield analysis with no building present; the second (OMF) includes a full masonry building on the surface made from 2D facades; thirdly, surface beams with properties determined using the equivalent elastic beam method are used to represent the building (OEB); and finally the building is represented by equivalent masonry surface beams (OMB).

Table 8.8: **Description of finite element run types for oblique analyses**

FE Run Name	Description of Analysis
OGF	Oblique Greenfield
OMF	Oblique with building made of 2D Masonry Facades
OEB	Oblique with Equivalent Elastic Beams representing the building
OMB	Oblique with Equivalent Masonry Beams representing the building

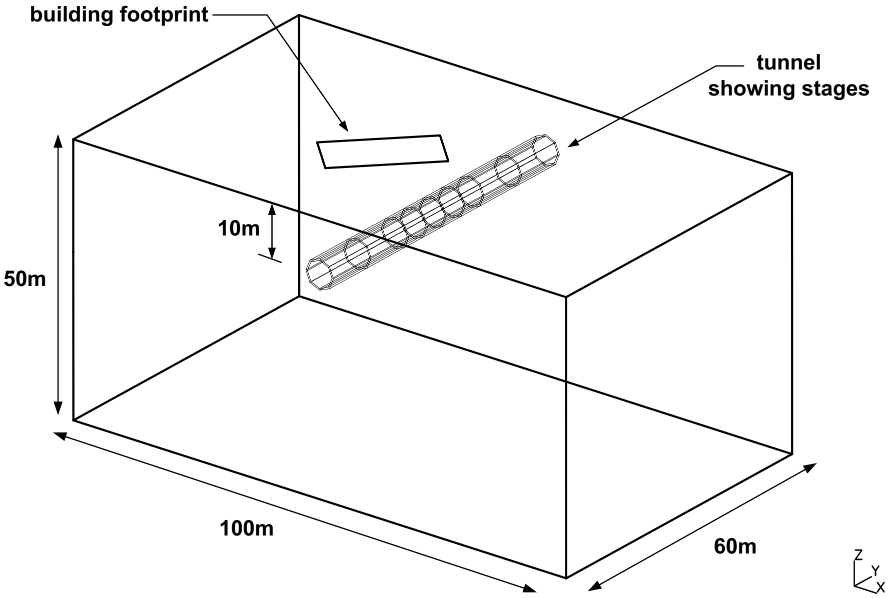


Figure 8.25: **Oblique example analysis layout**

Geometry, mesh and material properties

Figure 8.25 shows the layout of the oblique example problem. As for the symmetric analysis, it consists of a 5m inner diameter tunnel located 10m below ground level. On the surface is the same 20m long, 10m wide and 8m high masonry building with 1m thick walls shown in figure 8.2. The tunnel lining is again 0.25m thick and the applied volume loss is 2%. The soil block for the problem is 100m wide, 50m high and 60m long as shown. The building is located on the surface such that the facades are oriented at 45^o to the tunnel alignment and the centre line of the tunnel passes under the front facade at a point 4.5m from the end wall as shown in figure 8.26.

The soil mesh for all the oblique analyses is shown in figure 8.27(a) with the building mesh for the full front and rear facades and end walls for run type OMF shown in figures 8.27(b) and 8.27(c). The soil and tunnel mesh contains 12682 nodes and 8612 ten-noded tetrahedral elements; for run type OMF, the building mesh has 1938 nodes and 836 six-noded triangular plane stress elements; and for run types OEB and OMB, the surface beams comprise 62 Timoshenko beam elements. The boundary conditions applied to the soil are: fully fixed displacements (x, y and z displacements fixed) at the base and horizontal displacements (x or y displacements as appropriate) fixed perpendicular to each vertical

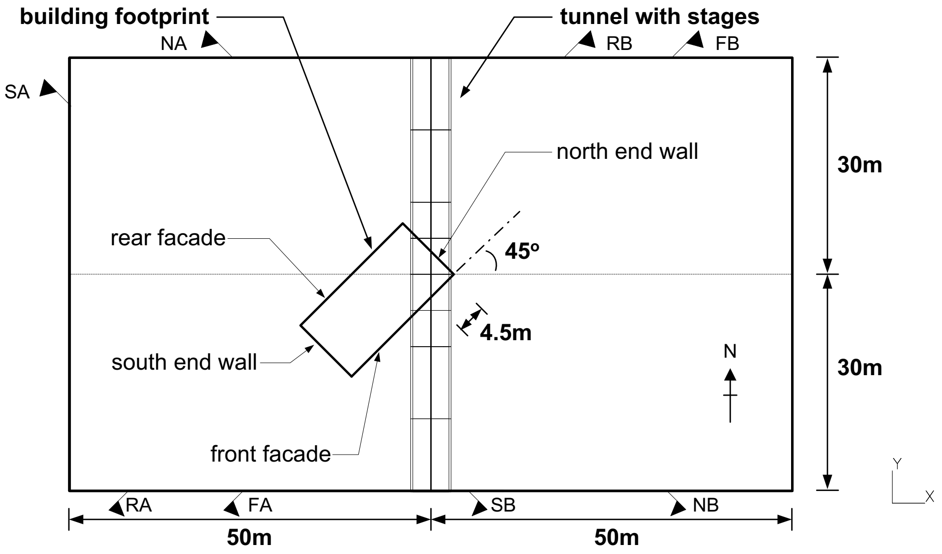


Figure 8.26: **Plan of oblique example problem**

soil boundary.

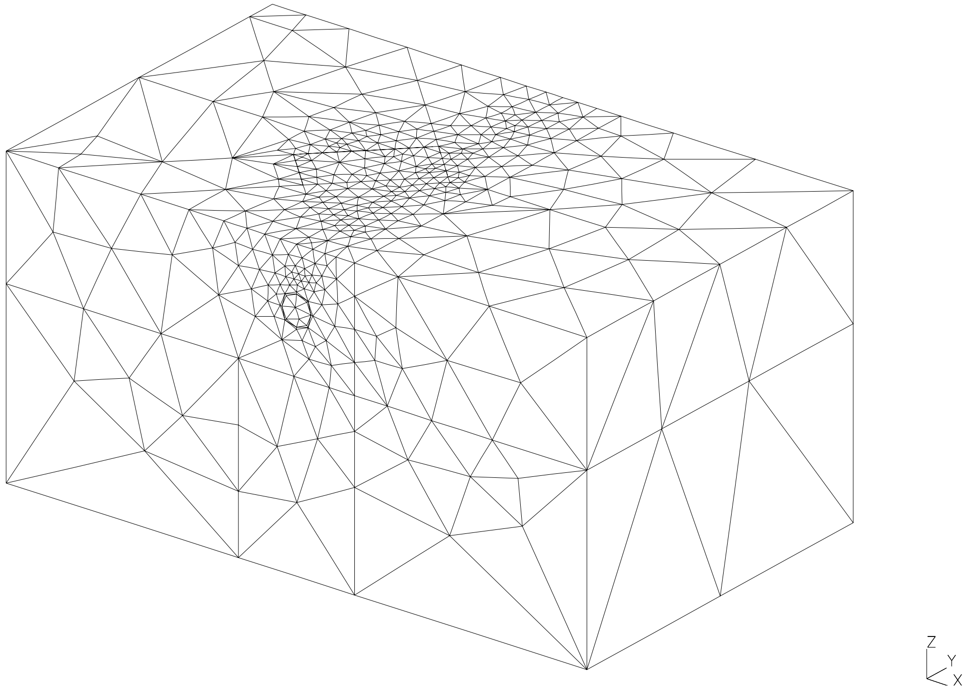
The material properties assigned to the soil, tunnel, building facades and surface beams are identical to those used for the symmetric analyses and are given in section 8.2.1 above.

Calculation procedure

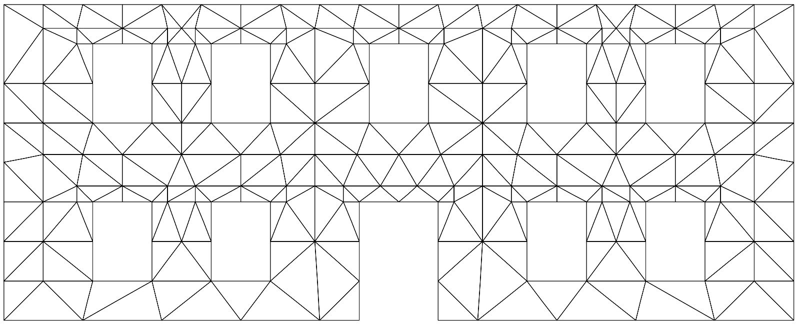
The calculation proceeds in stages similar to the symmetric analyses except that the the tunnel for the oblique analyses is constructed in eight stages. Table 8.9 shows the calculation stages and the construction lengths used for the oblique analyses.

As for the symmetric analyses there are two exceptions to the general procedures: the setting of the residual tensile strength for the masonry facades, c, to 0.0kPa while the building self weight is applied to the model (stages 1 and 2 in table 8.9), the residual tensile strength is then changed to 10kPa at the commencement of tunnelling (stage 3); and the addition of the masonry beam elements only after stage 2 is complete. Both are designed to avoid stress accumulating in the facades or beams during the self weight loading distorting the displacements due to tunnelling in the later stages.

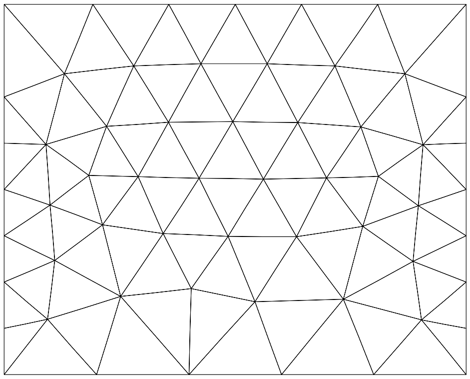
The number of calculation steps per stage is chosen as 15 steps (Wisser, 2002) for all analyses except the OMB analyses where the number of steps chosen to reduce the out of



(a) All oblique analyses: Soil mesh



(b) Analysis OMF: Building front and rear facade mesh



(c) Analysis OMF: Building end walls mesh

Figure 8.27: **Oblique example analysis soil mesh**

Table 8.9: **Calculation stages for oblique example analysis**

Stage	No. Steps	Description
1	15	Application of building weight and initial soil stresses
2	10	Reset displacements and strains to zero
3	15 (30 for OMB)	Tunnel construction stage 1: 0.0 - 10.0m
4	15 (30 for OMB)	Tunnel construction stage 2: 10.0 - 20.0m
5	15 (30 for OMB)	Tunnel construction stage 3: 20.0 - 25.0m
6	15 (30 for OMB)	Tunnel construction stage 4: 25.0 - 30.0m
7	15 (30 for OMB)	Tunnel construction stage 5: 30.0 - 35.0m
8	15 (30 for OMB)	Tunnel construction stage 6: 35.0 - 40.0m
9	15 (30 for OMB)	Tunnel construction stage 7: 40.0 - 50.0m
10	15 (30 for OMB)	Tunnel construction stage 8: 50.0 - 60.0m

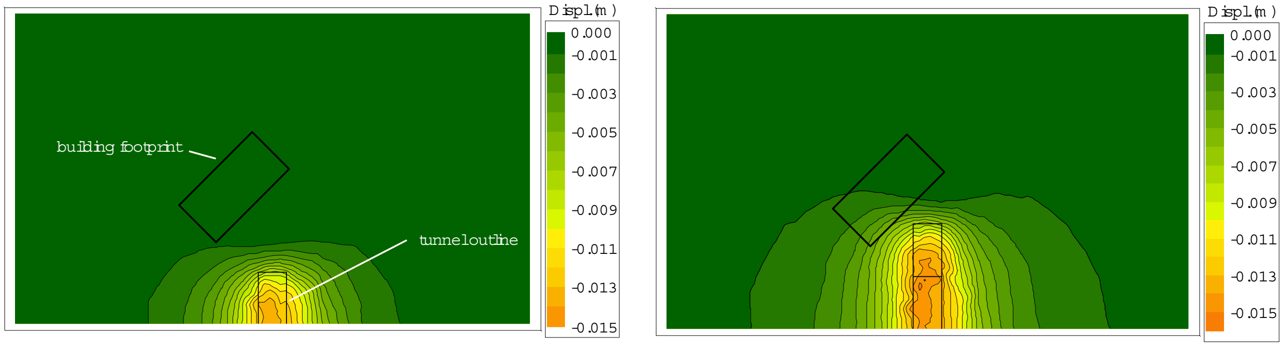
balance forces is 30 steps.

8.3.2 Greenfield analysis

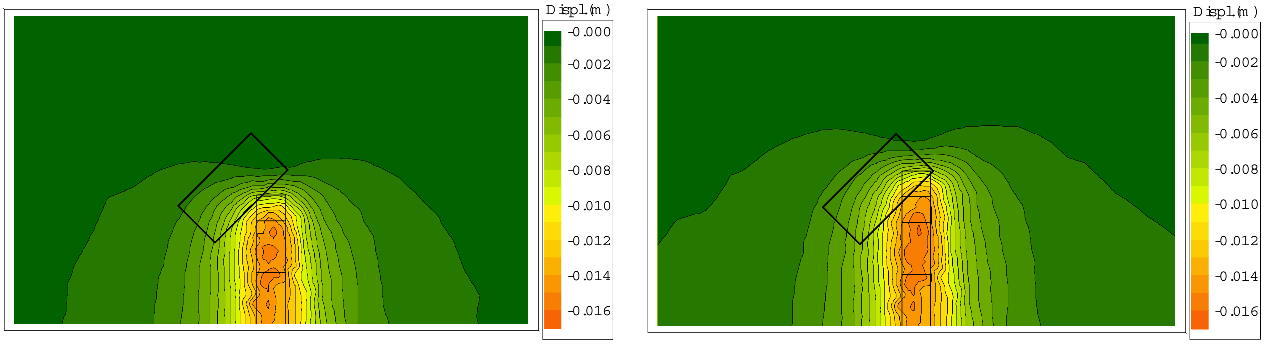
This section details the results of the greenfield run OGF with no building on the surface. Figure 8.28 shows the surface contours after each tunnelling stage, while figure 8.29 shows the surface profile development in 3D. Vertical surface displacements are shown in figure 8.30 along lines including: (a) the front facade (line FA-FB in figure 8.26); (b) rear facade (RA-RB); (c) north end wall (NA-NB); and (d) the south end wall (SA-SB), for each tunnelling stage.

The greenfield surface displacements for the oblique problem shown in figure 8.28 are not as smooth as the results for the symmetric problem from figure 8.5. Possible reasons for this are that the mesh for the oblique problem is coarser than for the symmetric problem, particularly at the surface over the tunnel centre line; and that with more tunnelling stages, in particular underneath the building footprint, the influence of the stage boundaries (Wisser, 2002) may be enhanced.

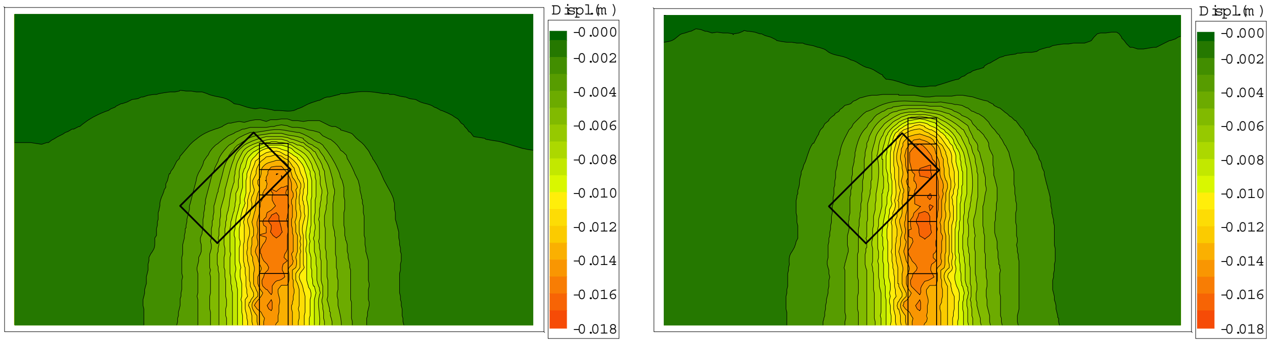
The greenfield finite element settlement trough is again shallower and wider than the Gaussian approximation with both curves being shown in figure 8.31. As with the symmetric problem, this feature does not limit the usefulness of the OGF run for use as a reference against which the influence of including a building on the surface, by means of facades



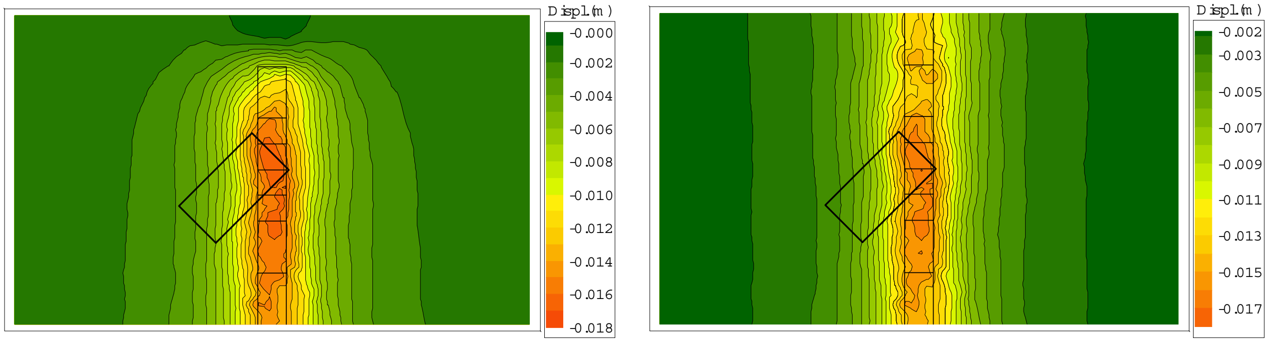
(a) Tunnelling Stage 1 (b) Tunnelling Stage 2



(c) Tunnelling Stage 3 (d) Tunnelling Stage 4

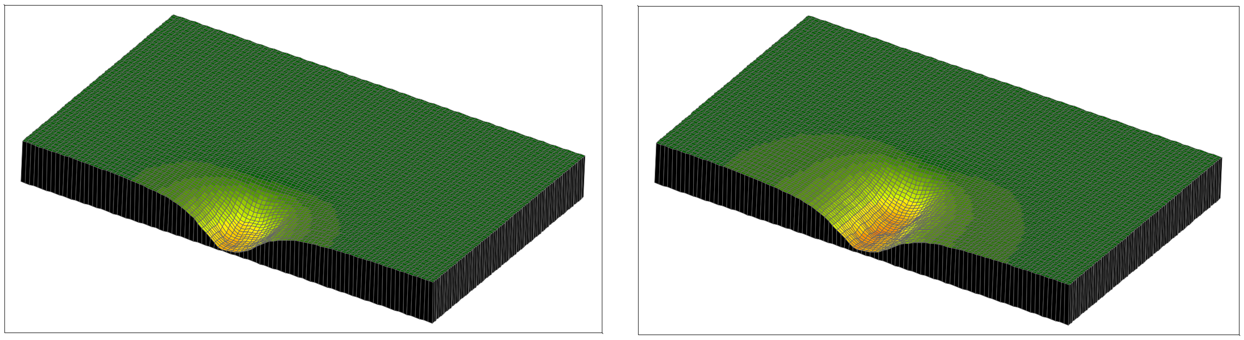


(e) Tunnelling Stage 5 (f) Tunnelling Stage 6

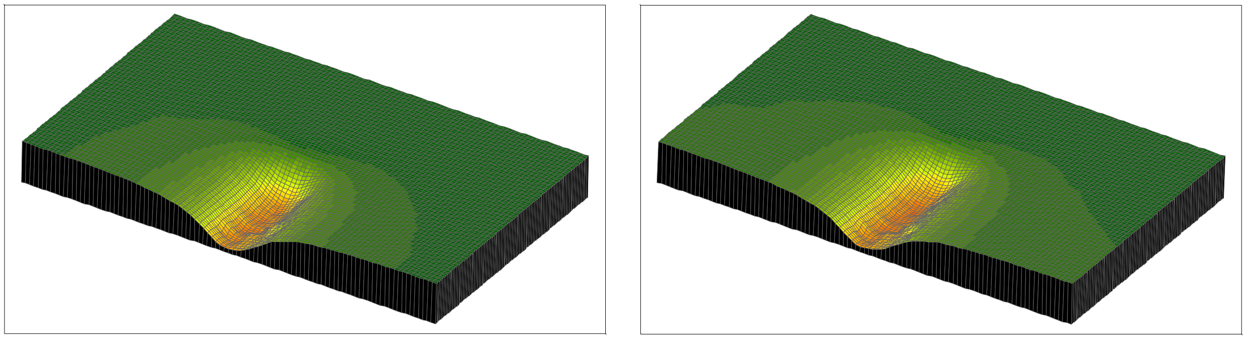


(g) Tunnelling Stage 7 (h) Tunnelling Stage 8

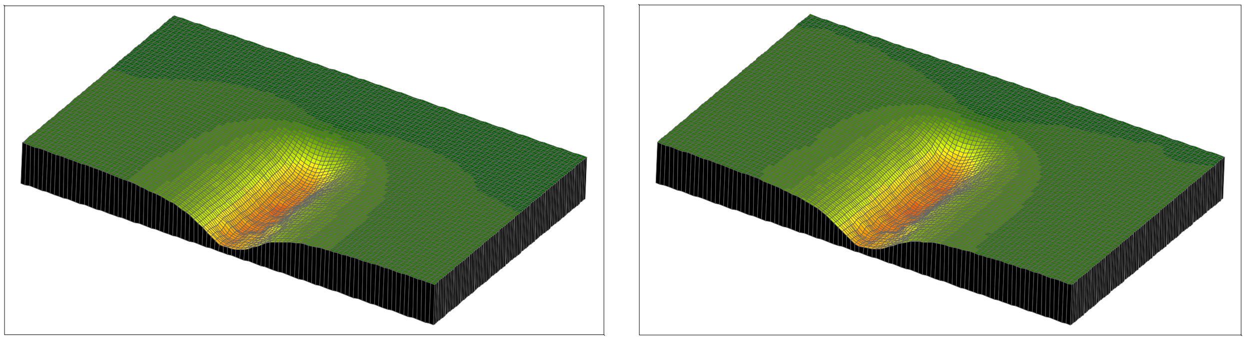
Figure 8.28: **Greenfield run OGF: Surface displacement contours**



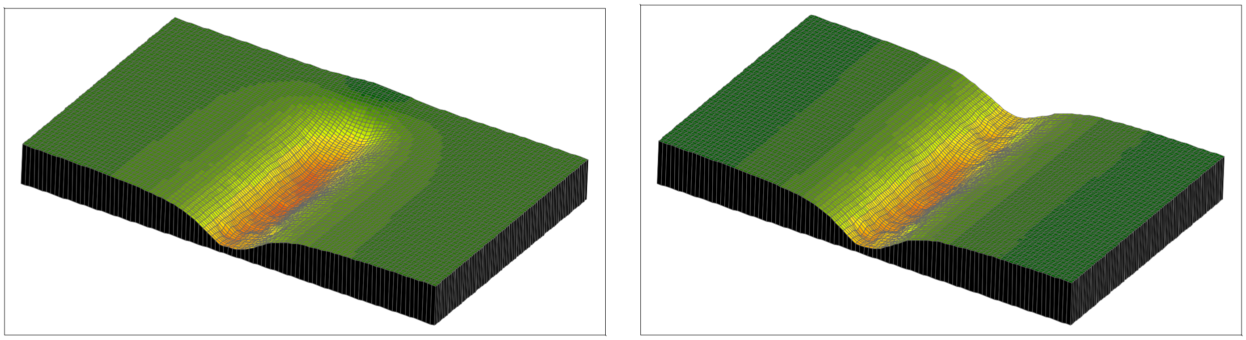
(a) Tunnelling Stage 1 (b) Tunnelling Stage 2



(c) Tunnelling Stage 3 (d) Tunnelling Stage 4

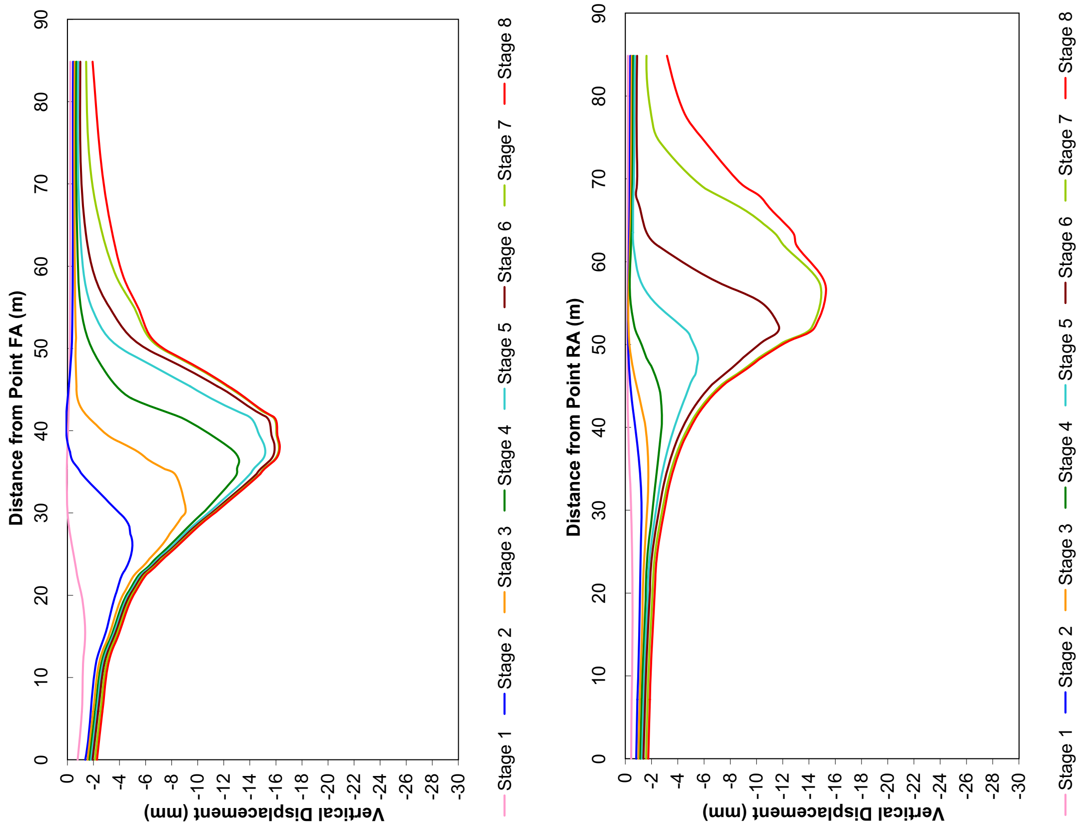


(e) Tunnelling Stage 5 (f) Tunnelling Stage 6

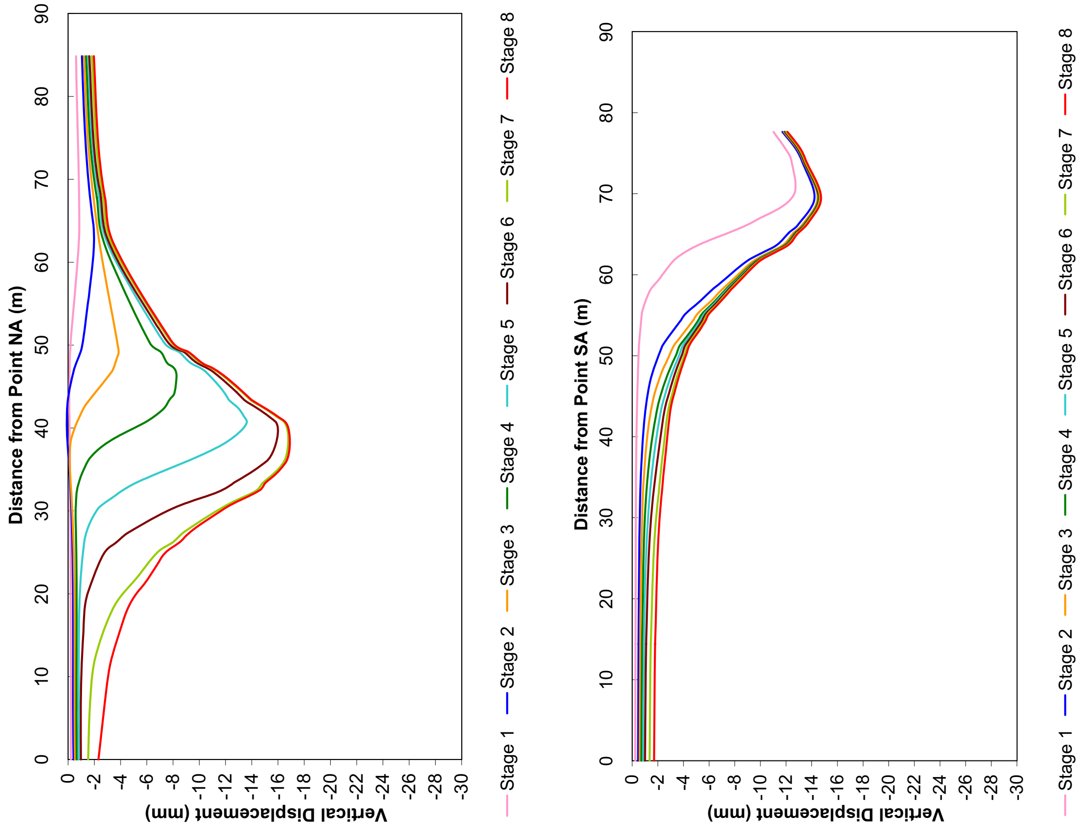


(g) Tunnelling Stage 7 (h) Tunnelling Stage 8

Figure 8.29: **Greenfield run OGF: 3D Surface profile**



(a) Front facade (b) Rear facade



(c) North end wall (d) South end wall

Figure 8.30: **Greenfield run OGF: Surface displacements**

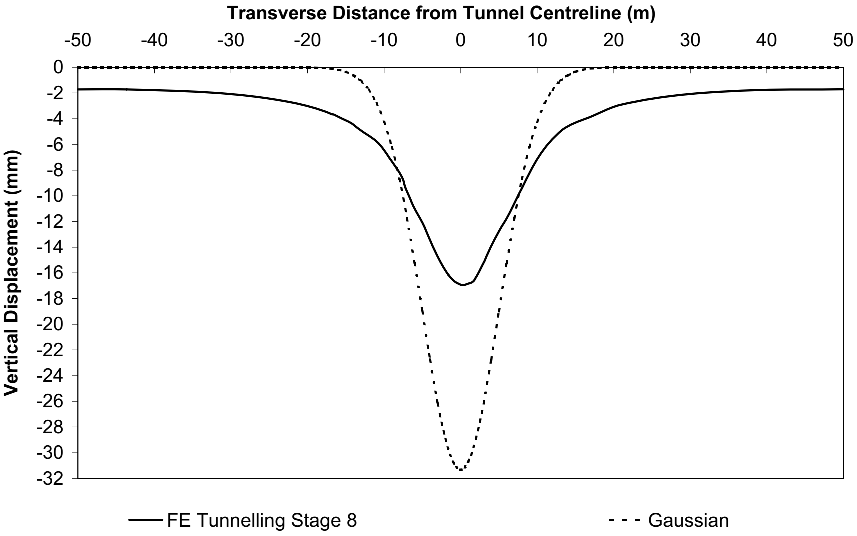


Figure 8.31: **Greenfield run SGF: Comparison with transverse Gaussian Settlement (y=30m)**

(OMF), or surface beams (OEB and OMB runs), can be compared.

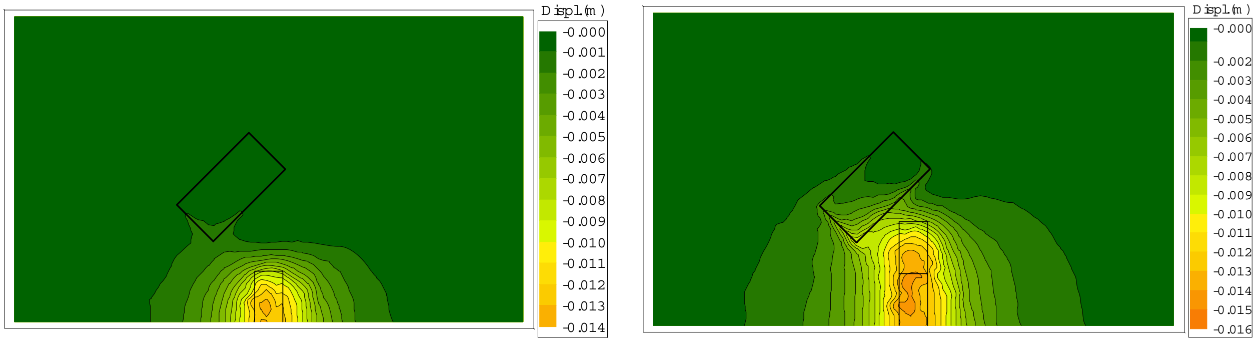
8.3.3 Analysis with masonry building

Surface displacement results from run type OMF with the building comprising 2D masonry facades are presented in figures 8.32 to 8.34.

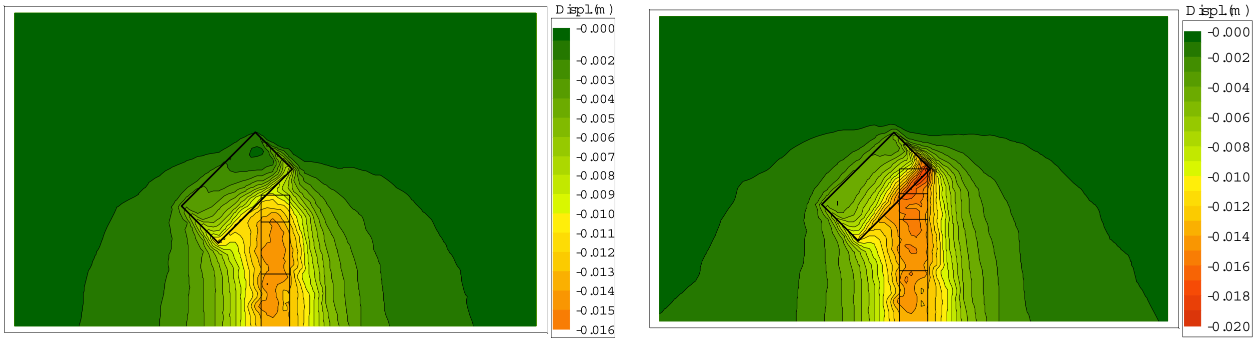
The influence of the building due to its self weight is clearly observable as the maximum settlement (under the corner of the front and north end walls) is 28.2mm (figure 8.34) compared to 16.9mm, the maximum settlement in the greenfield analysis (figure 8.30). The magnitude of the displacements along all walls are greater than those for the greenfield run.

The interaction of the building with the ground under each wall differs depending on the shape of the ground displacements under each individual wall. The front facade is mostly in a sagging region (with some slight hogging at the southern end). The response of the facade is essentially rigid for the first five tunnelling stages (figure 8.34(a)) with some slight hogging curvature developing in the final three stages (maximum Δ/L=0.004%).

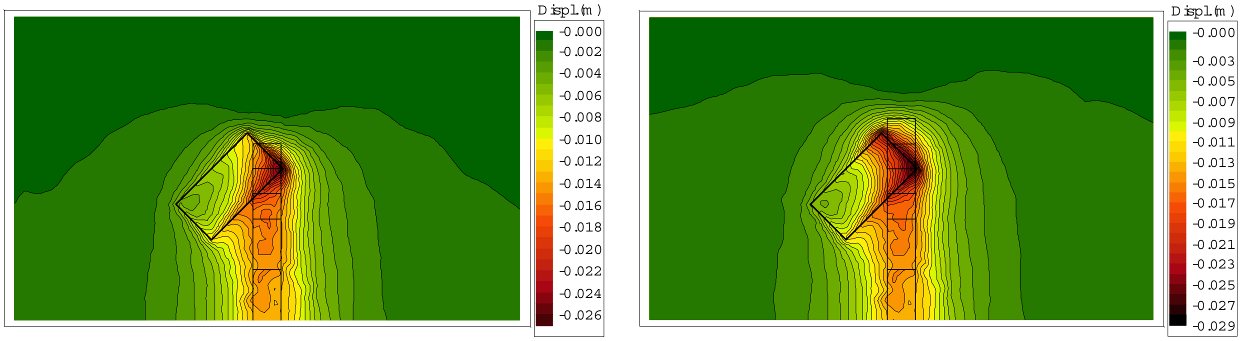
The rear facade is mostly in a hogging zone and displays significant hogging curvature as tunnelling develops (maximum Δ/L=0.027% in the final stage). The facade is much less



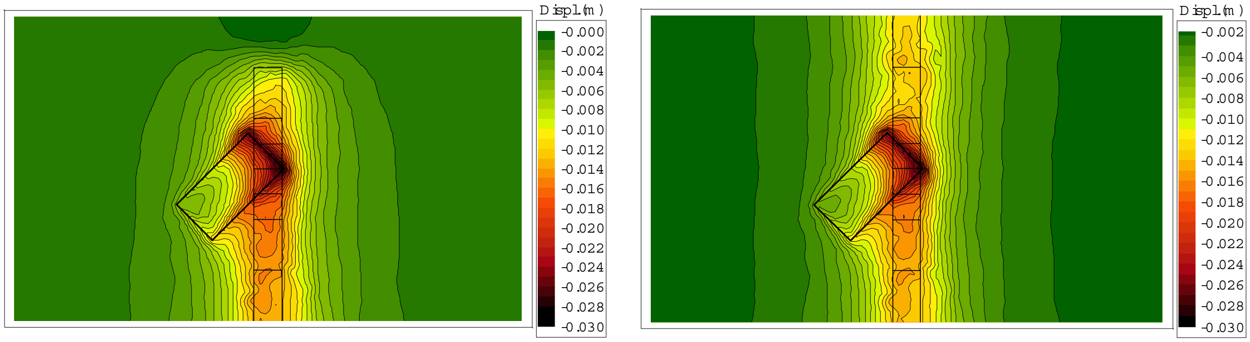
(a) Tunnelling Stage 1 (b) Tunnelling Stage 2



(c) Tunnelling Stage 3 (d) Tunnelling Stage 4

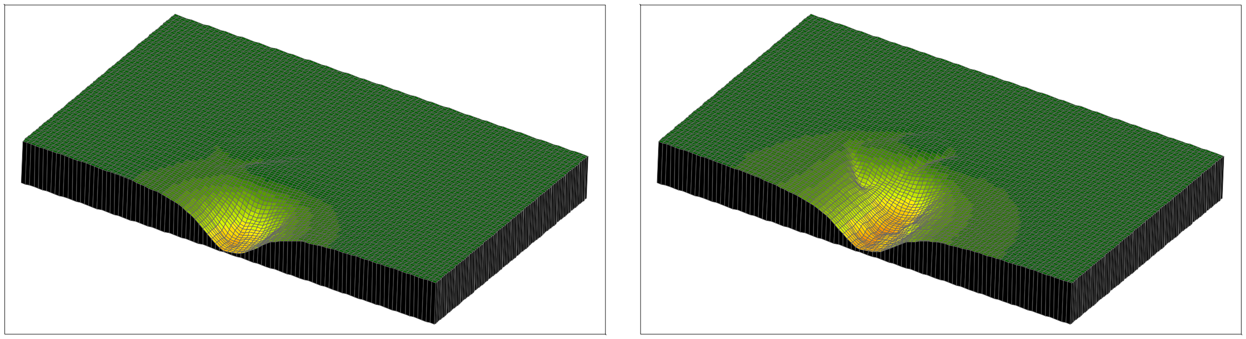


(e) Tunnelling Stage 5 (f) Tunnelling Stage 6

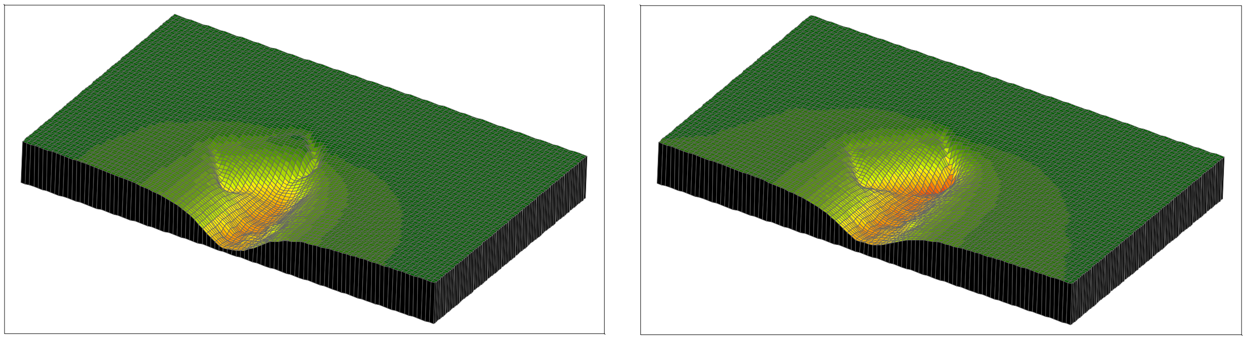


(g) Tunnelling Stage 7 (h) Tunnelling Stage 8

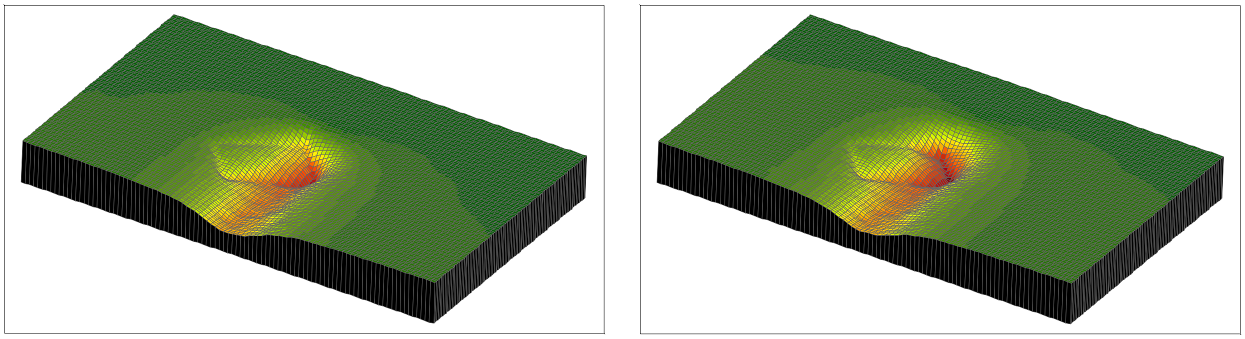
Figure 8.32: **Masonry building run OMF: Surface displacement contours**



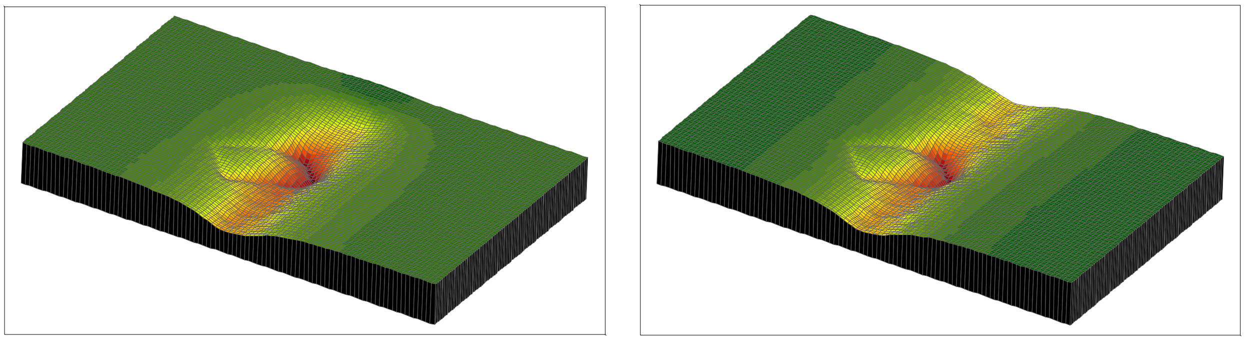
(a) Tunnelling Stage 1 (b) Tunnelling Stage 2



(c) Tunnelling Stage 3 (d) Tunnelling Stage 4

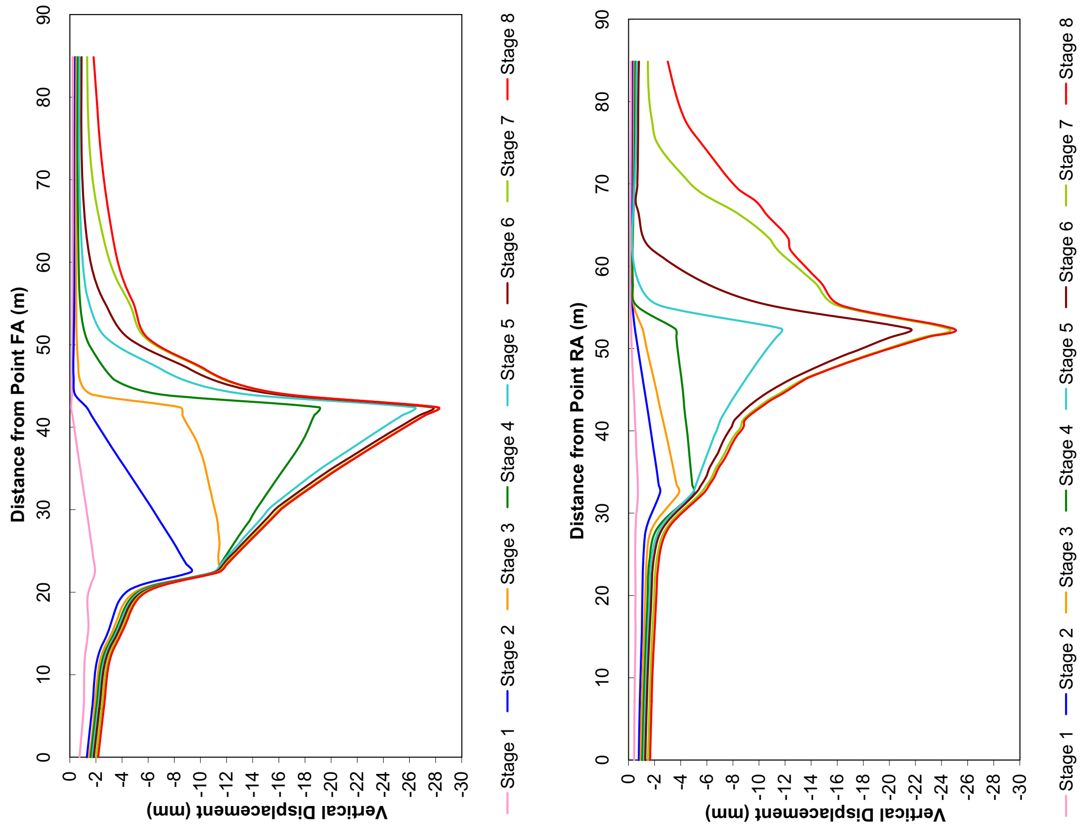


(e) Tunnelling Stage 5 (f) Tunnelling Stage 6

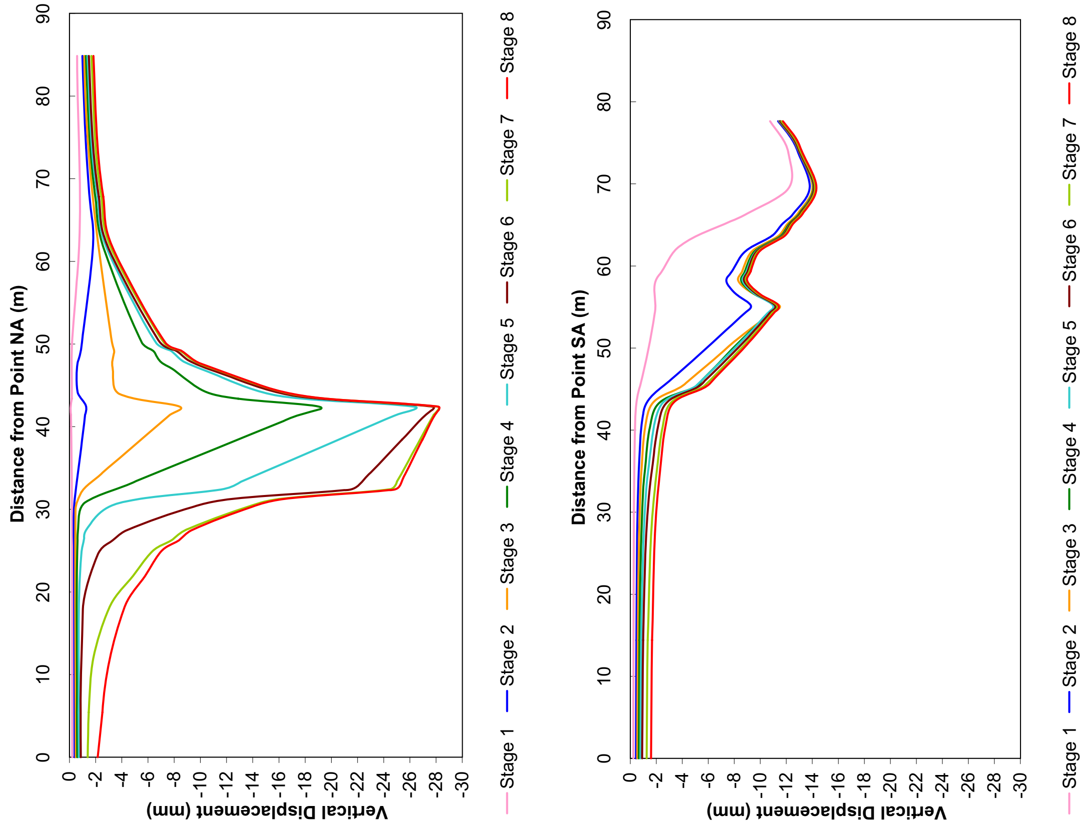


(g) Tunnelling Stage 7 (h) Tunnelling Stage 8

Figure 8.33: **Masonry building run OMF: 3D Surface profile**



(a) Front facade (b) Rear facade



(c) North end wall (d) South end wall

Figure 8.34: **Masonry building run OMF: Surface displacements**