

Table 8.6: **Analyses with equivalent elastic surface beams**

Analysis	Description
SEB	Properties given in tables 8.3 and 8.4
SEB2	As for SEB but with $EI_{in} \times 10$
SEB3	As for SEB but with $EI_{in} \times 1/5$
SEB4	As for SEB but with $EI_{in} \times 1/10$
SEB5	As for SEB but with $EI_{in} \times 1/100$
SEB6	As for SEB but with $EI_{in} \times 1/1000$
SEB7	As for SEB but with no self weight

8.2.4 Analysis with equivalent elastic surface beams

Results from run type SEB (symmetric run with equivalent elastic beams) are described in this section. Following the description of the initial run (SEB) which has elastic surface beams with properties as given in tables 8.3 and 8.4 representing the building, a range of analyses are used to investigate the impact of differing beam properties. These include the building weight and the in-plane bending stiffness assigned to the beams. The analyses described in this section are summarised in table 8.6.

Equivalent elastic surface beams

Results for run SEB are shown in figures 8.12 to 8.14. Building facades are represented by Timoshenko surface beams with equivalent elastic beam properties.

The results show the influence of the building weight adding to the magnitude of the surface displacements; the centre line vertical displacement of approximately 16mm being greater than the greenfield settlement of 14mm. In addition, the transverse settlement profile is again flattened compared to the greenfield profile. This is due to the relative stiffness of the elastic beams representing the building with respect to the soil. The transverse settlement under the beams (figures 8.14(a) and (b)) exhibits a flatter and smoother profile than the transverse settlement under the masonry facades (figures 8.11(a) and (b)). This is due to the fact that the beam has the same stiffness (and thus influence on the settlement profile) along its length leading to a smooth profile. The profile under the masonry facade, however, is influenced by the location of the windows and door openings and the arching

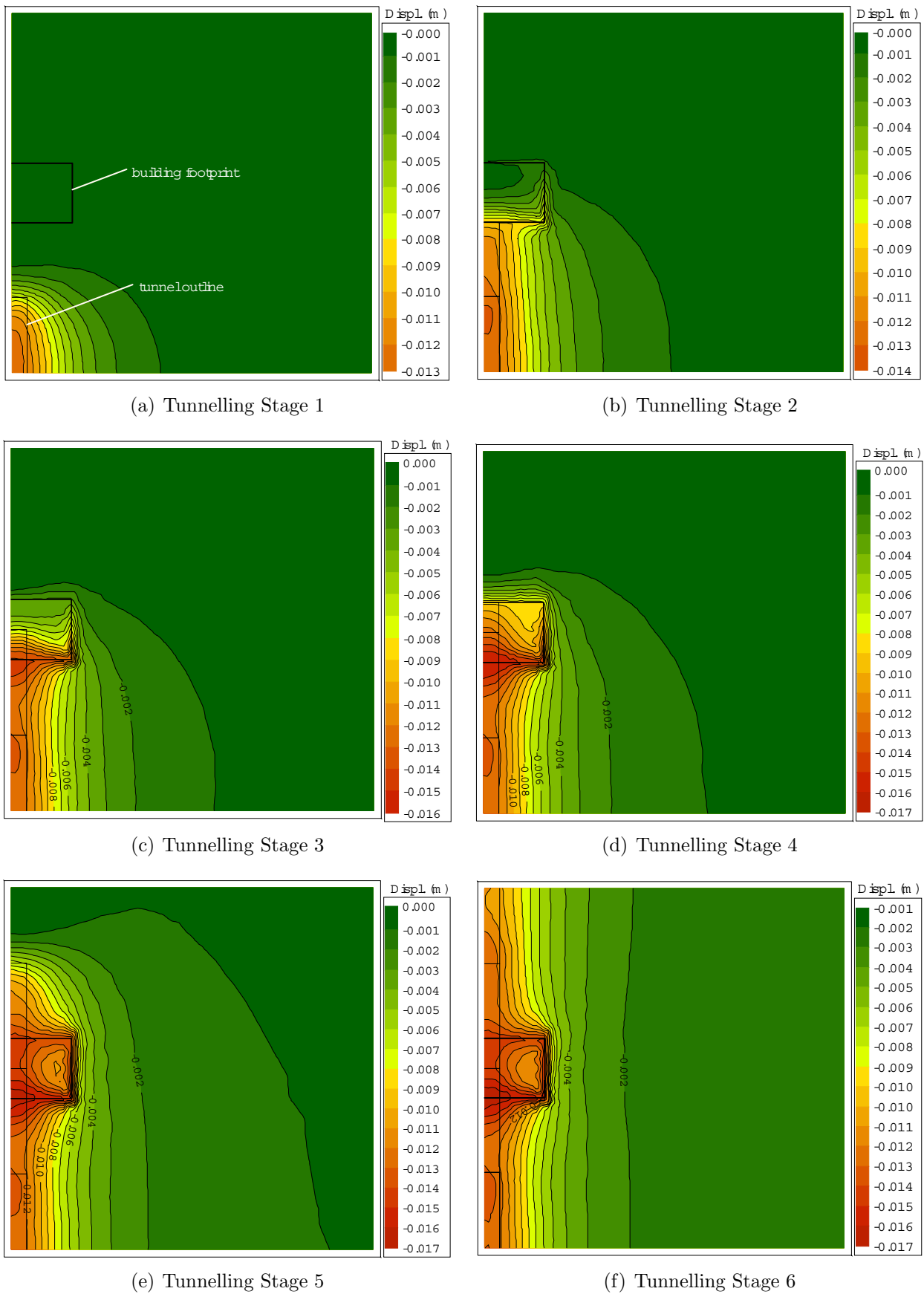
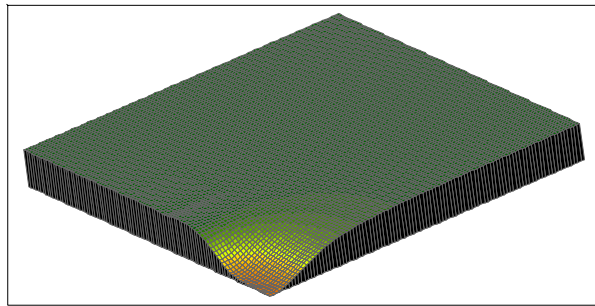
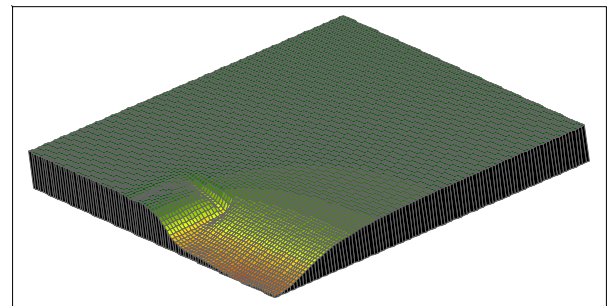


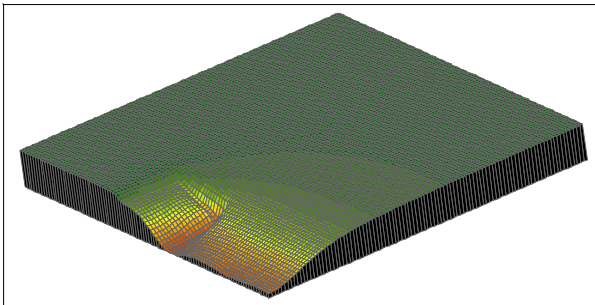
Figure 8.12: Equivalent elastic surface beams run SEB: Surface displacement contours



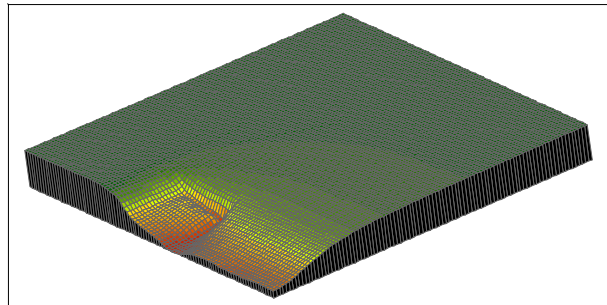
(a) Tunnelling Stage 1



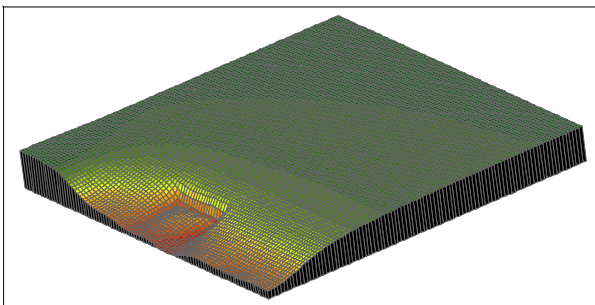
(b) Tunnelling Stage 2



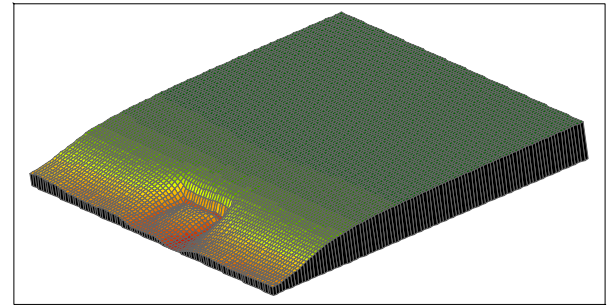
(c) Tunnelling Stage 3



(d) Tunnelling Stage 4



(e) Tunnelling Stage 5



(f) Tunnelling Stage 6

Figure 8.13: Equivalent elastic surface beams run SEB: 3D Surface profile

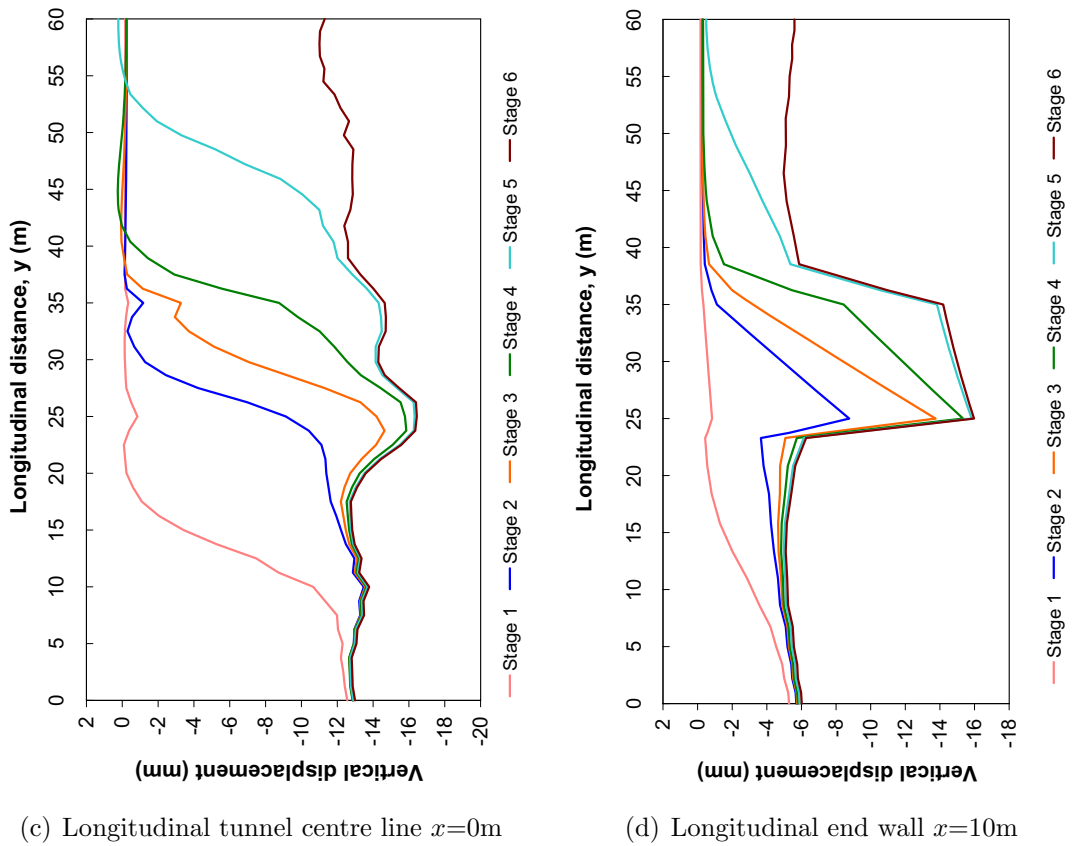
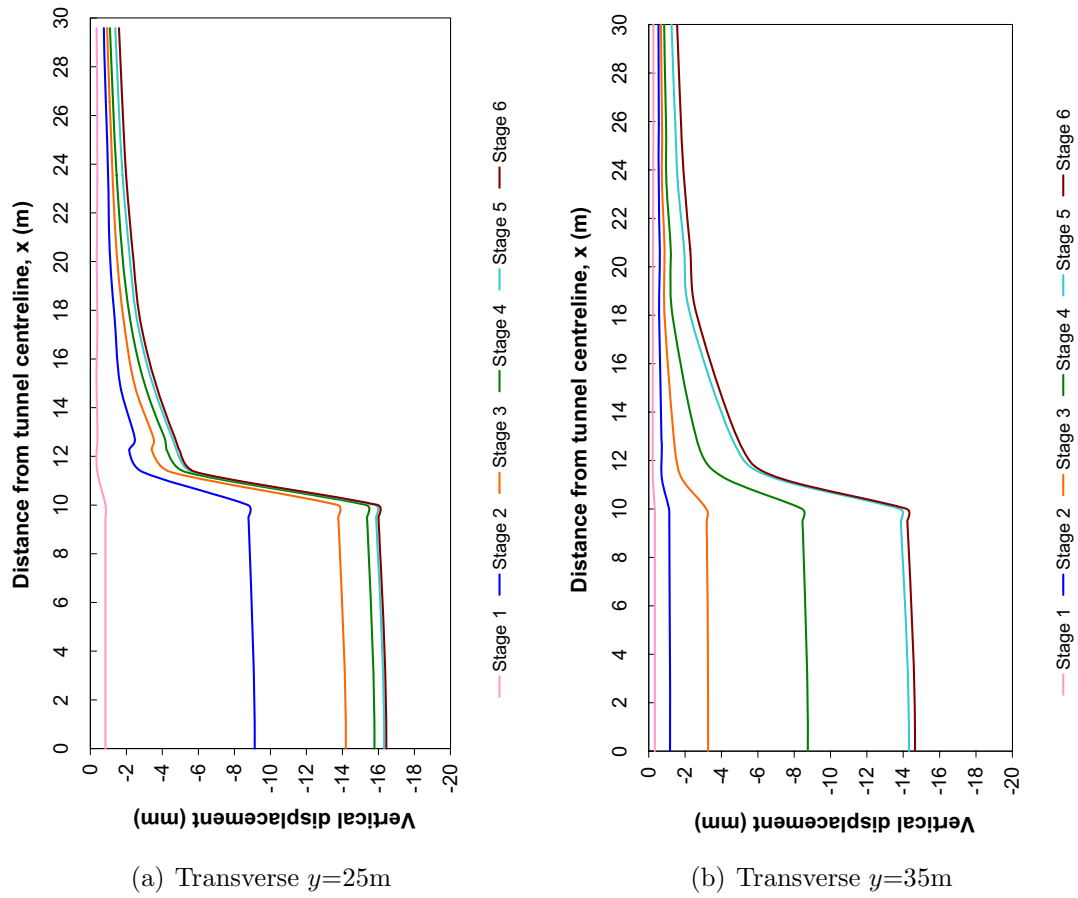


Figure 8.14: Equivalent elastic surface beams run SEB: Surface displacements

effect. The use of surface beams with equivalent elastic model properties thus gives a smooth approximation of the masonry facade response. The resulting surface displacements closely match the magnitude of the displacements under the masonry facades (from run SMF) but exhibit less variation along the facade length. The use of 3D surface beams with properties attributed using the equivalent elastic beam model can be seen to give closely comparable surface settlements to those under the full masonry facade for this problem.

Influence of building stiffness

Analysis SEB was repeated with the in-plane bending stiffness for the beams varied by using the multiples as shown in table 8.6 (runs SEB2 to SEB6). These multiples were used for the in-plane bending stiffness properties for the beams given in tables 8.3 and 8.4.

Figure 8.15 shows the surface displacements after the final tunnelling stage using surface beams with various in-plane bending stiffnesses. The effect of reducing the bending stiffness is clearly visible: it causes the profile to take a shape more like a greenfield profile, but with additional vertical displacement due to the self weight. The effects of reducing bending stiffness has been demonstrated previously by others (see section 2.5.4) including Potts and Addenbrooke (1997) and Jenck and Dias (2004). It is interesting to compare figures 8.15(a) and (b) with figure 2.10 which shows settlement profiles by Potts and Addenbrooke (1997) also tending towards the greenfield profile with reduction in bending stiffness. The only difference is that, no additional settlement due to the self weight is seen in figure 2.10 as this was not included in those results (self weight is included in the relative stiffness method subsequently by Franzius et al. (2004)). Jenck and Dias (2004) present similar results to those in figures 8.15(a) and (b) showing that increasing the stiffness of their building (by adding basement levels) causes the transverse settlement profile to be less like the greenfield.

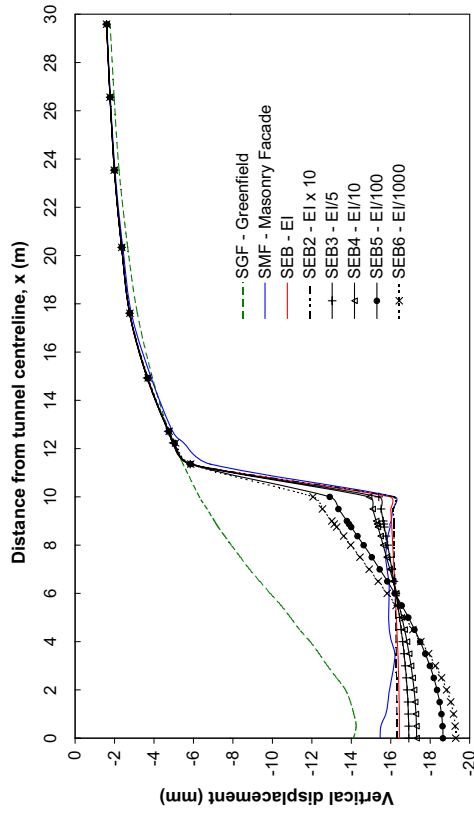
The initial analysis, SEB, exhibits similar surface settlements to run SEB2 (with ten times the stiffness) and it is these runs that most closely match the surface displacements of run SMF with the full masonry facades. The importance of using an appropriate properties

for elastic surface beams is thus apparent: if the bending stiffness of the beam is too low, the settlement profile does not reflect the appropriate influence of the building; if the properties are too high, the surface profile will be too flat, overstating the influence of the building. It is acknowledged that this problem would be less sensitive to changes in the building stiffness than a problem where displacements are applied directly to the facade or building, due to the soil structure interaction. The properties assigned to run SEB using the methods developed in Chapter 4 of this thesis are thus considered to be appropriate as this run most closely matches the displacement profile of the masonry facades.

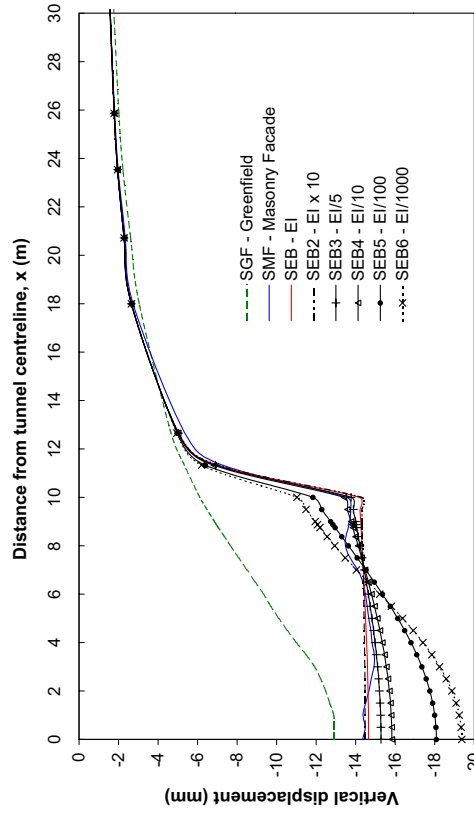
Influence of building weight

The influence of not including the building weight on the settlement profile due to tunnelling is investigated. Run SEB7 is identical to run SEB with the exception that the beams representing the building are assigned no self weight; all other properties of the beams are the same as those given in tables 8.3 and 8.4. Figures 8.16, 8.17 and 8.18 compare the surface contours, 3D surface profile and surface displacements for analysis SEB7 with no self weight and SEB with self weight.

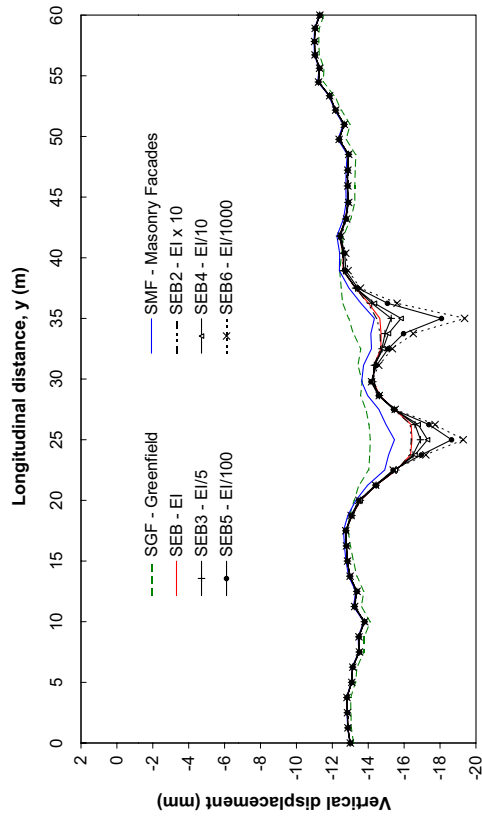
The influence of the building weight is apparent from the magnitude of the maximum settlement under the building. The maximum settlement of the front facade in run SEB7 of 9.6mm, is less than the in run SEB of 16.4mm with the building weight included. The observed effect of the building stiffness without the self weight, particularly evident in figure 8.17 is to reduce the settlement under the beams, relative to the greenfield situation (maximum settlement of 14.1mm). The importance of including the building weight in these analyses is thus apparent in terms of settlement prediction. This concurs with the investigation into the effects of different building weights by Liu (1997). It is interesting that Franzius et al. (2004) note that although building weight slightly influences the Potts and Addenbrooke (1997) modification factors, the stiffness of the building is a much more significant factor for predicting accurate building damage.



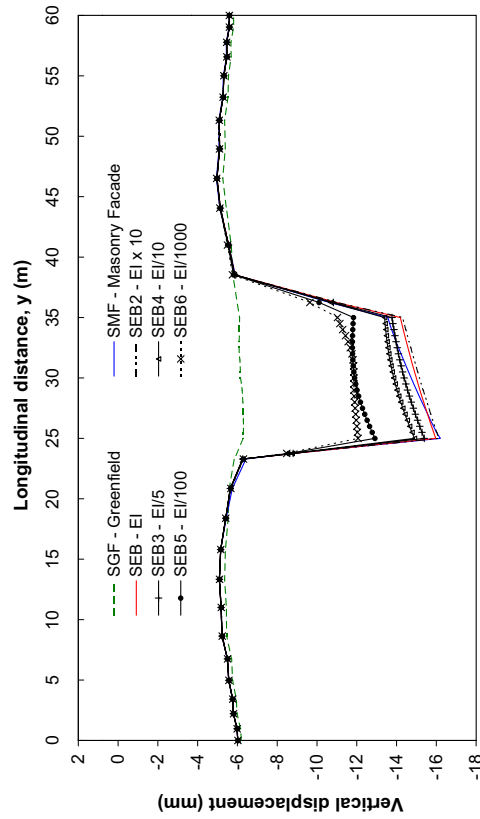
(a) Transverse $y=25\text{m}$



(b) Transverse $y=35\text{m}$

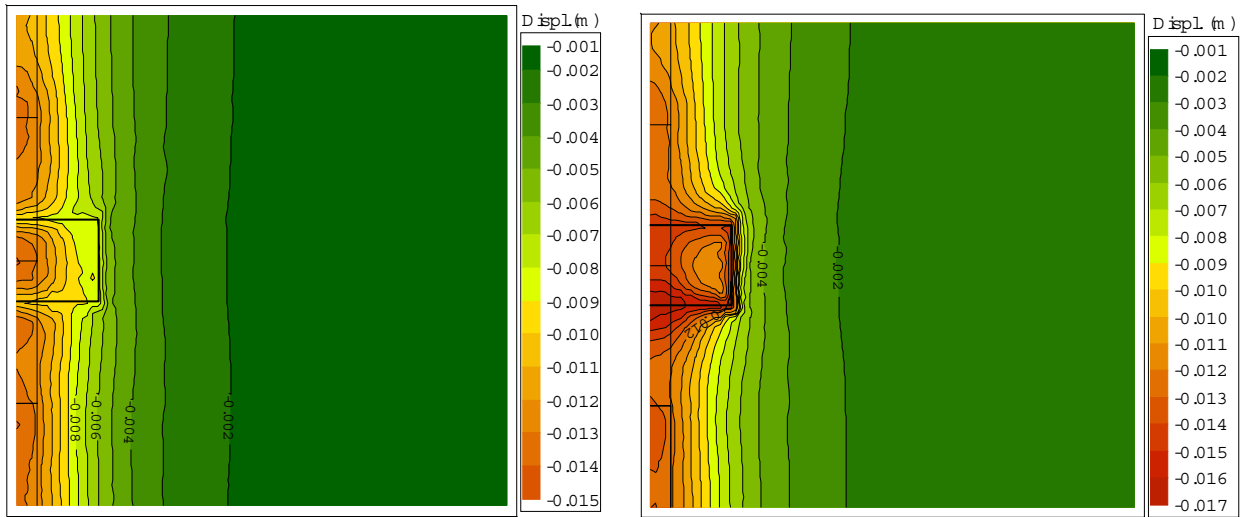


(c) Longitudinal tunnel centre line $x=0\text{m}$



(d) Longitudinal end wall $x=10\text{m}$

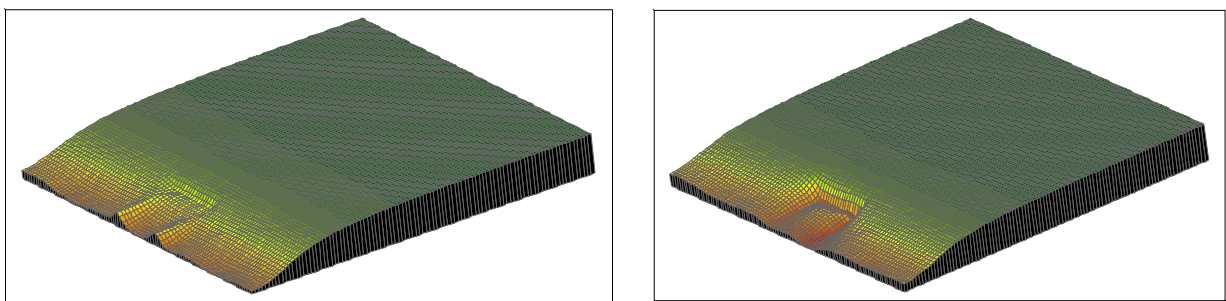
Figure 8.15: Equivalent elastic surface beams (Tunnelling Stage 6): Influence of bending stiffness



(a) SEB7 No self weight - Tunnelling Stage 6

(b) SEB With self weight - Tunnelling Stage 6

Figure 8.16: Equivalent elastic surface beams run SEB7 with no self weight: Surface displacement contours compared to run SEB with self weight



(a) SEB7 No self weight - Tunnelling Stage 6

(b) SEB With self weight - Tunnelling Stage 6

Figure 8.17: Equivalent elastic surface beams run SEB7 with no self weight: 3D Surface profile compared to run SEB with self weight

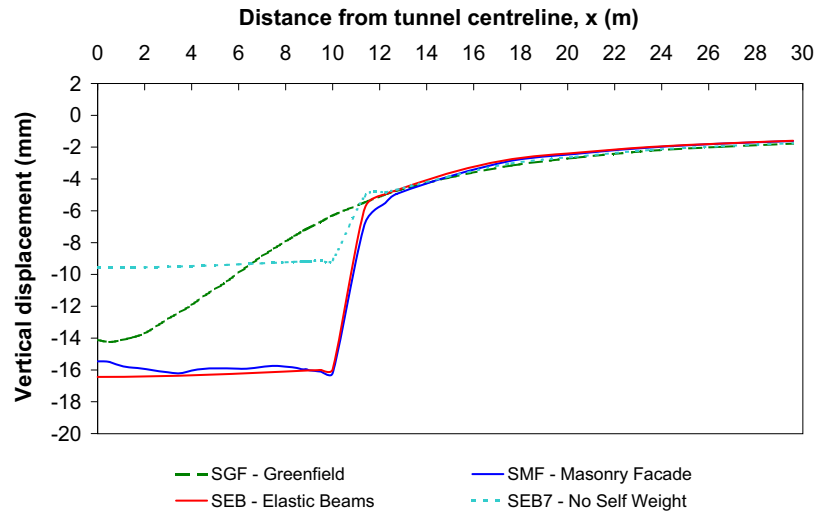


Figure 8.18: **Equivalent elastic surface beams: Surface displacements comparison ($y=25\text{m}$)**

8.2.5 Analysis with equivalent masonry surface beams

Results from run type SMB (symmetric run with equivalent masonry beams) are described in this section. Following the description of the central run (SMB22) which has masonry surface beams with properties as given in tables 8.3 and 8.4 representing the building, a range of analyses are used to investigate the impact of differing beam properties. These include the critical curvature, κ_{crit} and residual bending stiffness factor, f_b assigned to the beams. The analyses described in this section are summarised in table 8.7.

Equivalent masonry surface beams

Results from run SMB22 are described in this section. Results are shown in figures 8.19 to 8.21 for the run with the building facades represented by Timoshenko beams with equivalent masonry beam material with the properties given in tables 8.3 and 8.4. The parameters of critical curvature, κ_{crit} and residual bending stiffness factor, f_b for this central run (of the parametric study) were chosen as 1.0×10^{-5} and 0.010 respectively. These base case values were chosen based on a range of pre-calculations and preliminary analyses. The effect of the choice of these values for κ_{crit} and f_b is further discussed below.

The results again show the influence of the beams flattening the settlement profile and

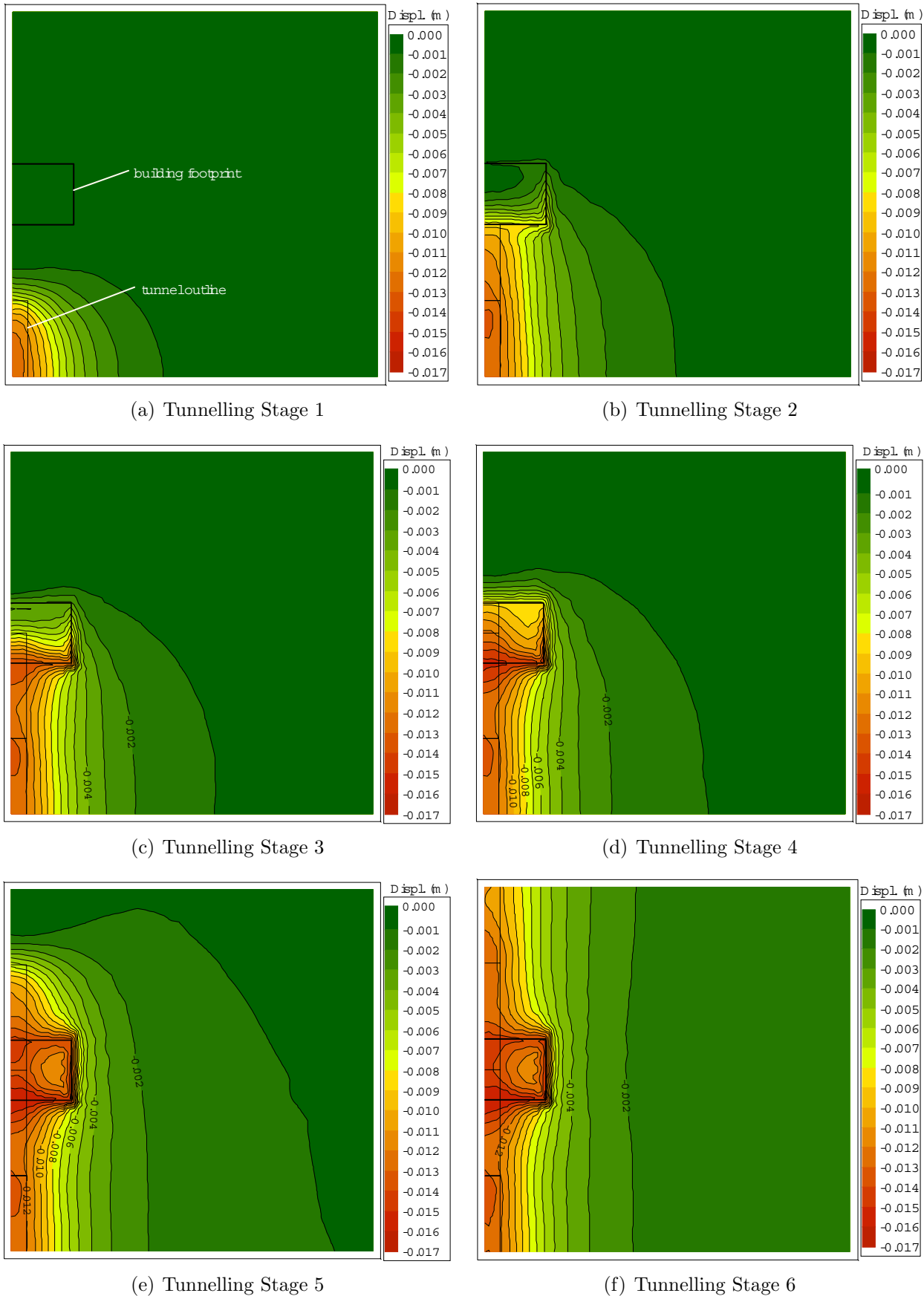
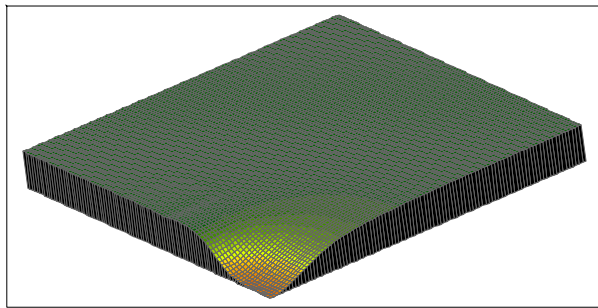
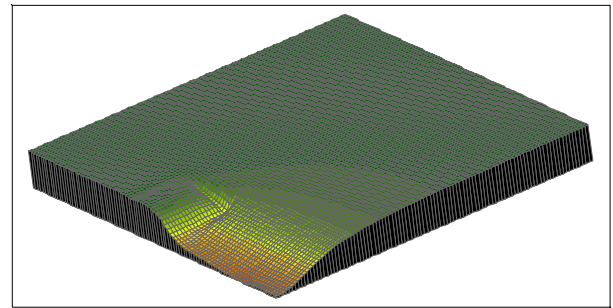


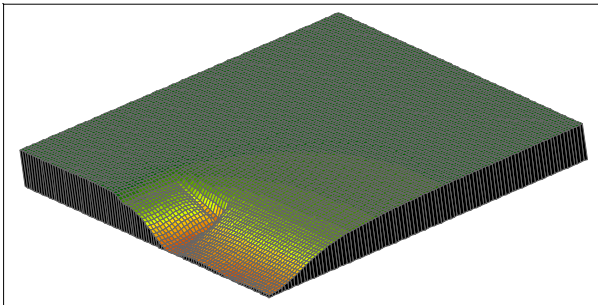
Figure 8.19: **Equivalent masonry surface beams run SMB: Surface displacement contours**



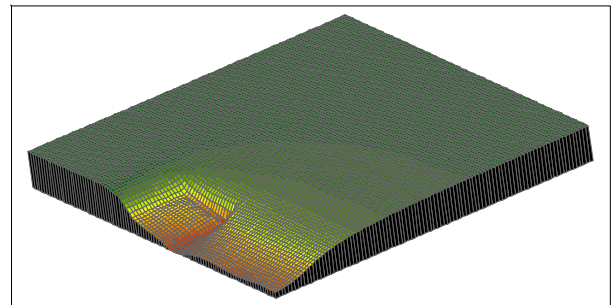
(a) Tunnelling Stage 1



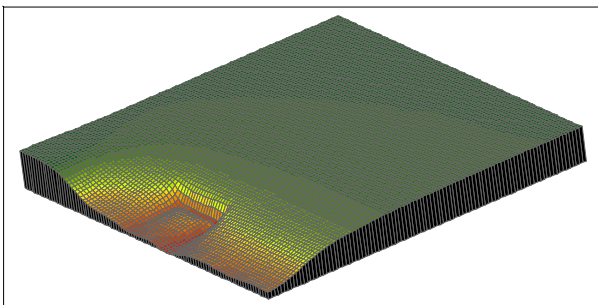
(b) Tunnelling Stage 2



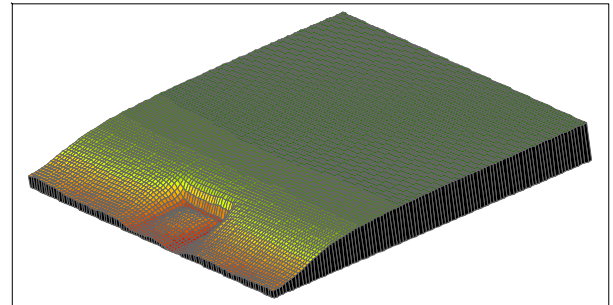
(c) Tunnelling Stage 3



(d) Tunnelling Stage 4



(e) Tunnelling Stage 5



(f) Tunnelling Stage 6

Figure 8.20: Equivalent masonry surface beams run SMB: 3D Surface profile

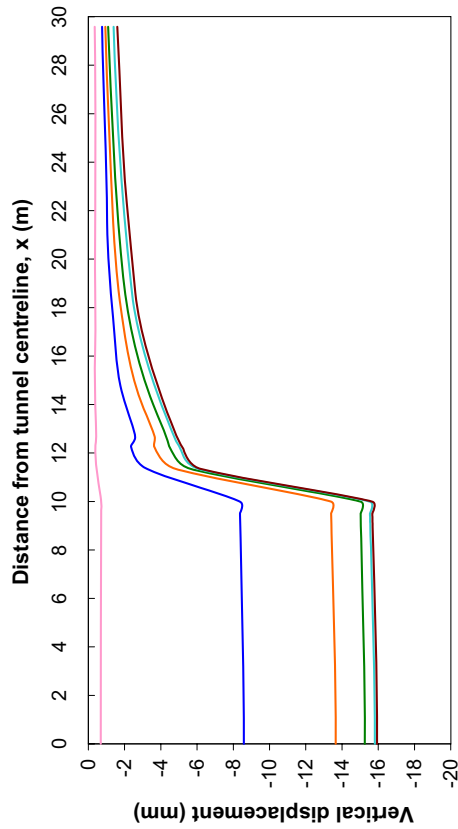
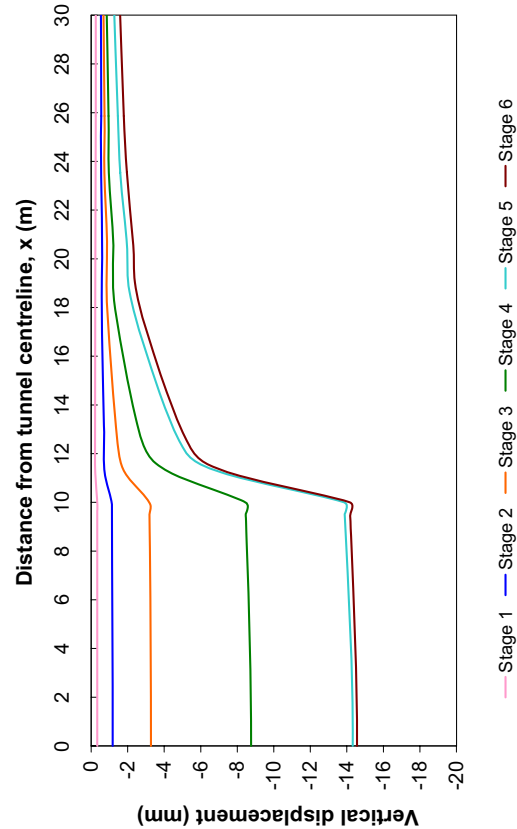
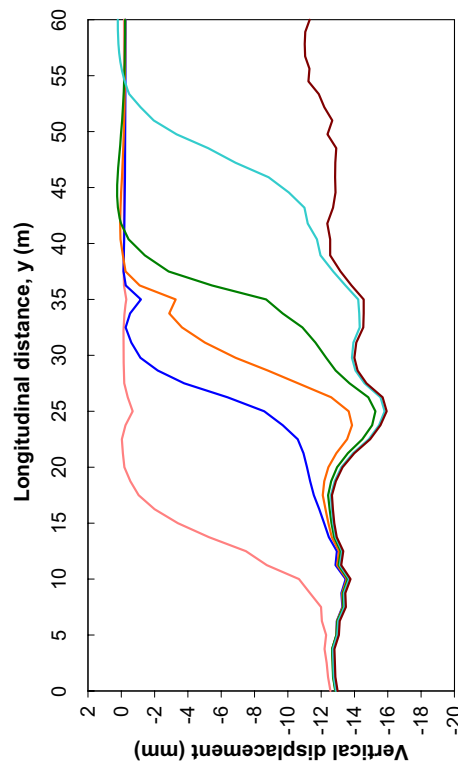
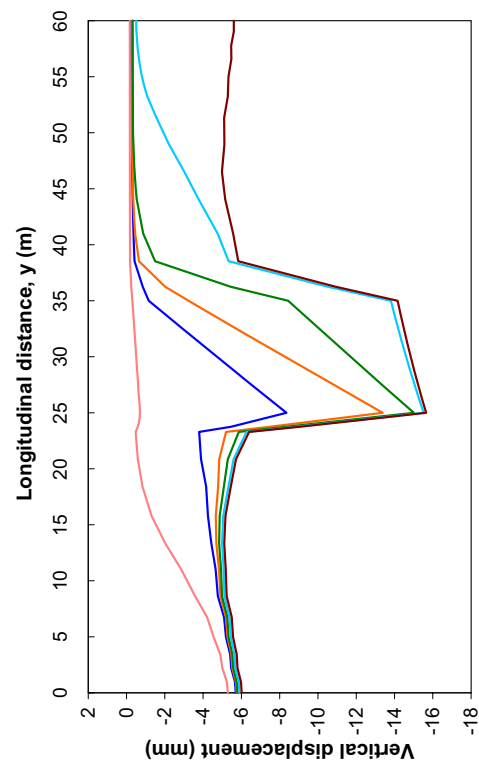
(a) Transverse $y=25\text{m}$ (b) Transverse $y=35\text{m}$ (c) Longitudinal tunnel centre line $x=0\text{m}$ (d) Longitudinal end wall $x=10\text{m}$

Figure 8.21: Equivalent masonry surface beams run SMB: Surface displacements

Table 8.7: Parameters for equivalent masonry beams

Analysis	κ_{crit}	f_b
SMB11	1.0×10^{-4}	0.100
SMB12	1.0×10^{-4}	0.010
SMB13	1.0×10^{-4}	0.001
SMB21	1.0×10^{-5}	0.100
SMB22	1.0×10^{-5}	0.010
SMB23	1.0×10^{-5}	0.001
SMB31	1.0×10^{-6}	0.100
SMB32	1.0×10^{-6}	0.010
SMB33	1.0×10^{-6}	0.001

the additional vertical settlement due to the building weight. The shape of the transverse settlement profile is almost identical to that from the the SEB run with the equivalent elastic beams. The majority of the facade is in the sagging zone where the in-plane bending stiffness of the equivalent masonry beam model remains constant and thus it is unsurprising that the surface displacement results are the same as the SEB run. As with run SEB, the settlement profile closely resembles that under the masonry facade in run SMF but is smoother and flatter.

Influence of κ_{crit} and f_b

The influence of the critical curvature, κ_{crit} and residual bending stiffness factor, f_b used in the equivalent masonry beam model is investigated in this section. Analysis type SMB was repeated using the range of different parameters shown in table 8.7. All other properties for the beams remained the same as those given in tables 8.3 and 8.4.

The choice of values for the parameters of f_b and κ_{crit} is influenced by a number of factors. Figure 8.22 shows theoretical moment-curvature diagrams for an equivalent masonry beam (EMB) in hogging. Moment-curvature plots including gradual stiffness reduction (as used in the EMB model and described in section 5.4.3) are shown along with bi-linear curves that would result from not using the gradual reduction of stiffness approach.

The choice of the residual bending stiffness (f_b) is driven by the aim of reducing the bending stiffness of the EMB in hogging to an appropriate level. It can be seen in figure

8.22(a) that the smaller the value of f_b , the greater the change in slope of the bi-linear target moment-curvature path and the tighter the gradually reducing stiffness curve. The incremental nature of the calculation procedure means that as lower values of f_b are used, greater out-of-balance forces will develop in each incremental load step. To keep the out-of-balance forces within reasonable limits a greater number of steps per stage may be required for lower values of f_b . The number of steps per stage used in these analyses is 30 steps compared to the 15 steps for the other analysis types in this thesis.

The choice of the appropriate value of f_b can be based on the equivalent elastic beam results for walls in hogging. These will be further discussed in the oblique example analysis section 8.3.4 as there is not a significant hogging section of wall in the symmetric analysis to draw any conclusions. For this analysis a value of $f_b=0.01$ is used (meaning that as hogging develops, the incremental stiffness in hogging trends towards 1% of the incremental stiffness in sagging).

The choice of the value of κ_{crit} also influences the shape of the load path as shown in figure 8.22(b). The smaller the critical curvature, the closer the change in stiffness of the moment-curvature path is to the origin, the sharper the corner in the load path. This again has an impact on the development of out-of-balance forces during the incremental calculation with greater out-of-balance forces developing for smaller values of κ_{crit} . Thus, the smaller the critical curvature selected, the greater the number of calculation steps required in each stage.

The choice of the value of κ_{crit} is based on the premise that there is a small hogging curvature that the masonry facade can sustain before cracking reduces its bending stiffness (as described in section 5.4.3). This point is the critical curvature, however, in the formulation of the EMBs a gradual reduction of stiffness approach is used to simulate the development of cracking leading to loss of stiffness, and to reduce the out of balance forces developed at this point. The range of values tested for κ_{crit} (in table 8.7) is designed to be appropriate for this analysis, although it would be worthwhile future work to investigate smaller values of κ_{crit} or the sudden reduction in stiffness approach.

Figure 8.23 shows the surface displacements after the final tunnelling stage with the various

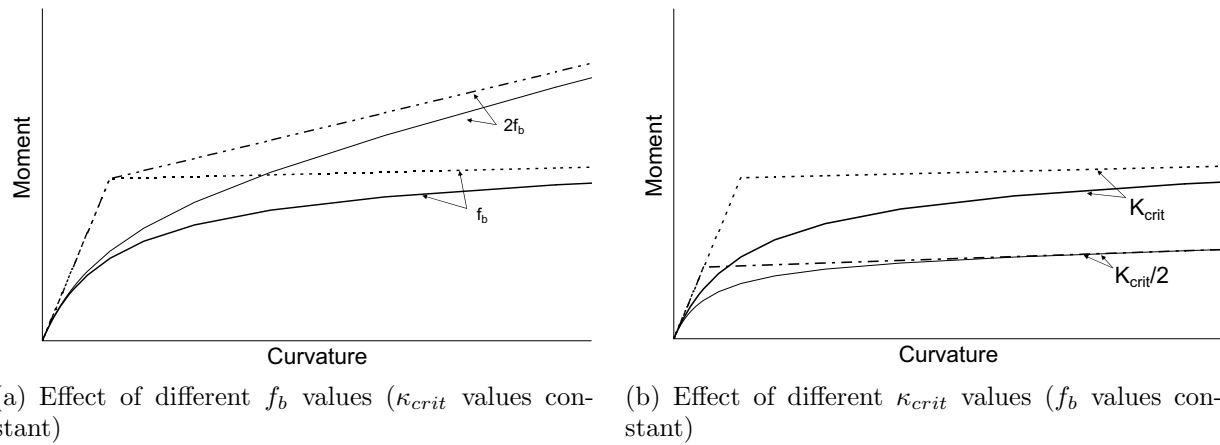
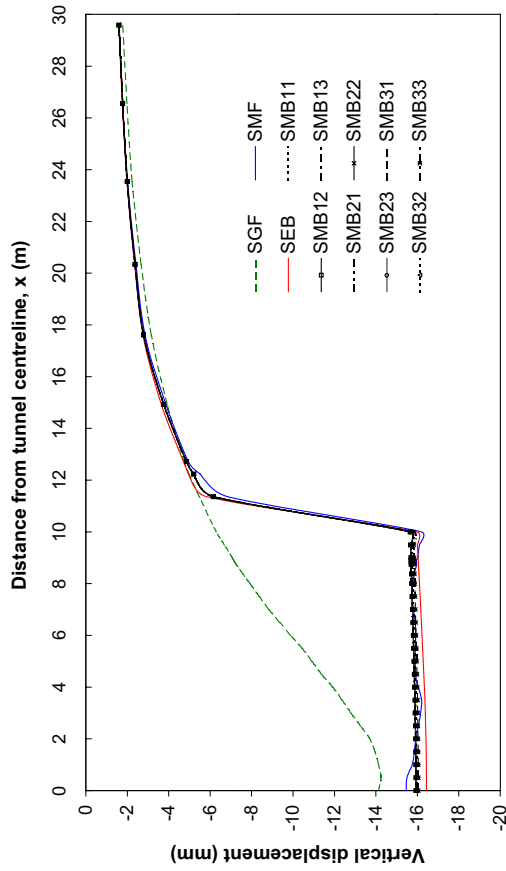


Figure 8.22: **Impact of differing residual bending stiffness (f_b) and critical curvature (κ_{crit}) values**

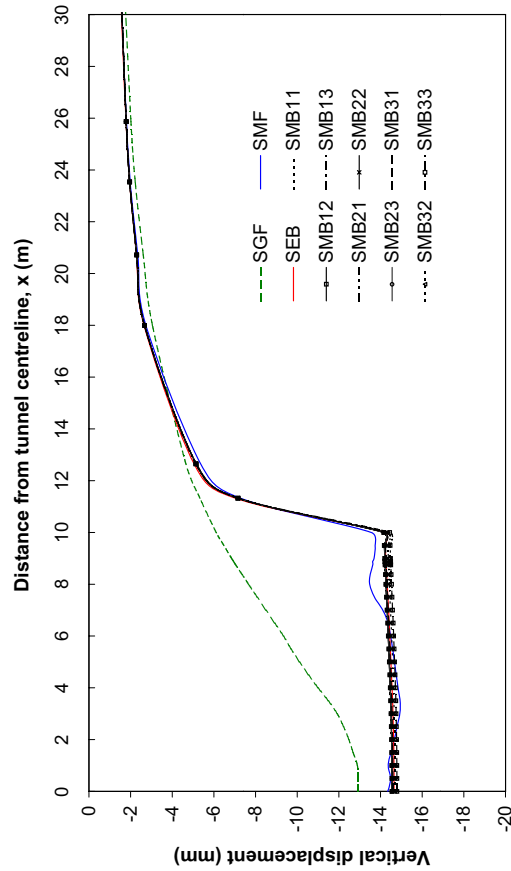
parameters from table 8.7 attributed to the beams. There is little observable difference between the transverse or centreline longitudinal settlements for all the runs.

There is an observable difference in the response of the end wall ($x=10\text{m}$) however. This wall is in a slight hogging mode throughout the tunnel construction. It can be seen that for runs SMB32 and SMB33, the beams lose bending stiffness and the wall hogs significantly more than the masonry facade or the masonry beam analyses. This indicates that the critical curvature for these beams could be considered to be too small, and that they are losing their stiffness too rapidly.

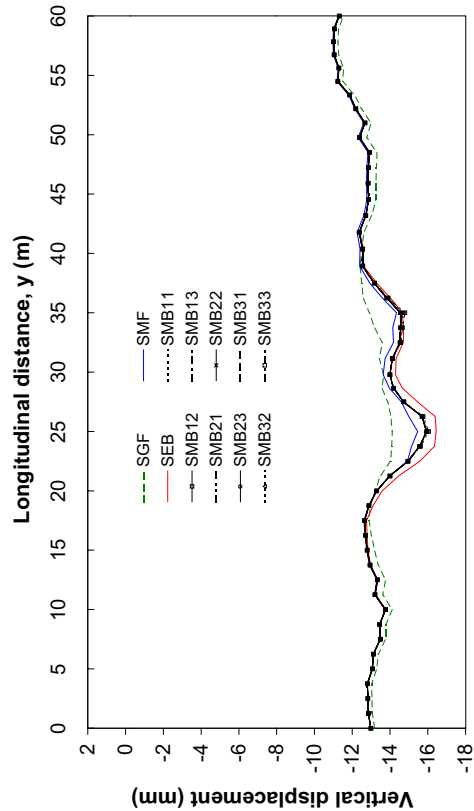
The amount by which the beam stiffness reduces is another consideration. SMB33 hogs significantly more than SMB32. The remainder of the runs do not hog significantly, similar to the masonry facade, but are all tilted to a different degree. This analysis does not allow any firm conclusions to be made regarding the parameters f_b and κ_c apart from the indication that a critical curvature of $\kappa_c=1.0 \times 10^{-6}$ may be too small as this causes the end wall to reduce its stiffness when the masonry facade does not. Further discussion of the choice of these parameters is given as part of the oblique analysis.



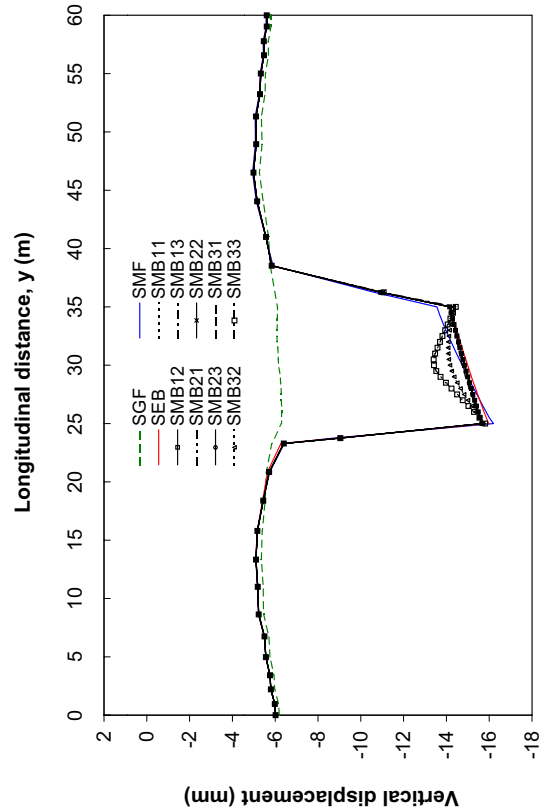
(a) Transverse $y=25\text{m}$



(b) Transverse $y=35\text{m}$



(c) Longitudinal tunnel centre line $x=0\text{m}$



(d) Longitudinal end wall $x=10\text{m}$

Figure 8.23: Equivalent masonry surface beams: Influence of κ_{crit} and f_b

Alternative equivalent masonry beam approach

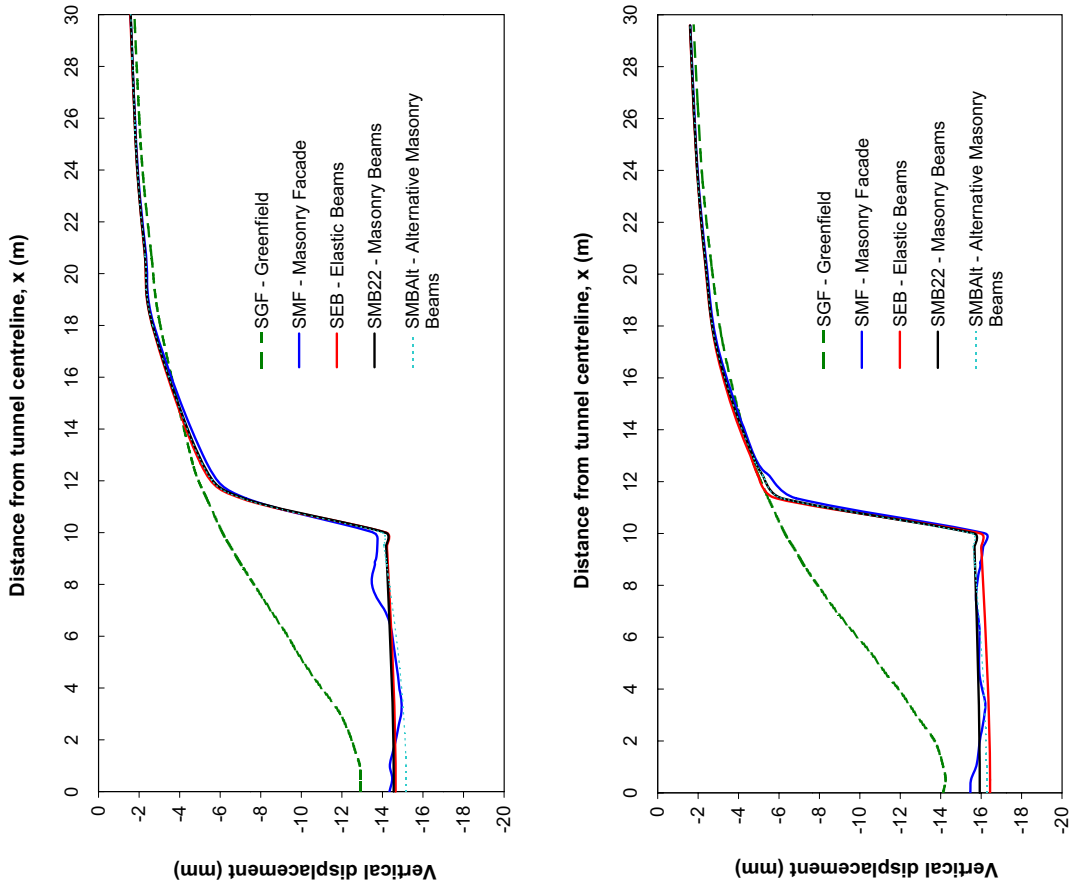
The settlement profile of surface beams using the alternative equivalent masonry beam model (outlined in section 5.4.4) is investigated in this section. This alternative approach involves the beams being assigned a reduced in-plane bending stiffness at the start of the analyses with which increases gradually if they go into a sagging mode of deformation. The settlement profile of equivalent masonry beams using both the standard and the alternative EMB approaches is compared to masonry facade, greenfield and equivalent elastic beam analyses in figure 8.24.

The alternative equivalent masonry beams can be seen to lead to a settlement profile that differs from the main EMBs. They are more flexible as a result of been assigned a low bending stiffness at the start of the analysis. This leads to their settlement profile differing from the masonry facade profile, in particular this can be seen in the end wall ($x=10\text{m}$) plot.

The problem with the alternative approach is that it does not allow for the existence of a threshold level of hogging bending strain which the masonry walls can sustain prior to their loss of stiffness. This is accounted for with the main EMB model through the critical curvature (κ_{crit}). The greater κ_{crit} , the more gradual is the reduction in bending stiffness. It is recommended that the main EMB model be used and the use of the alternative EMB approach be discontinued.

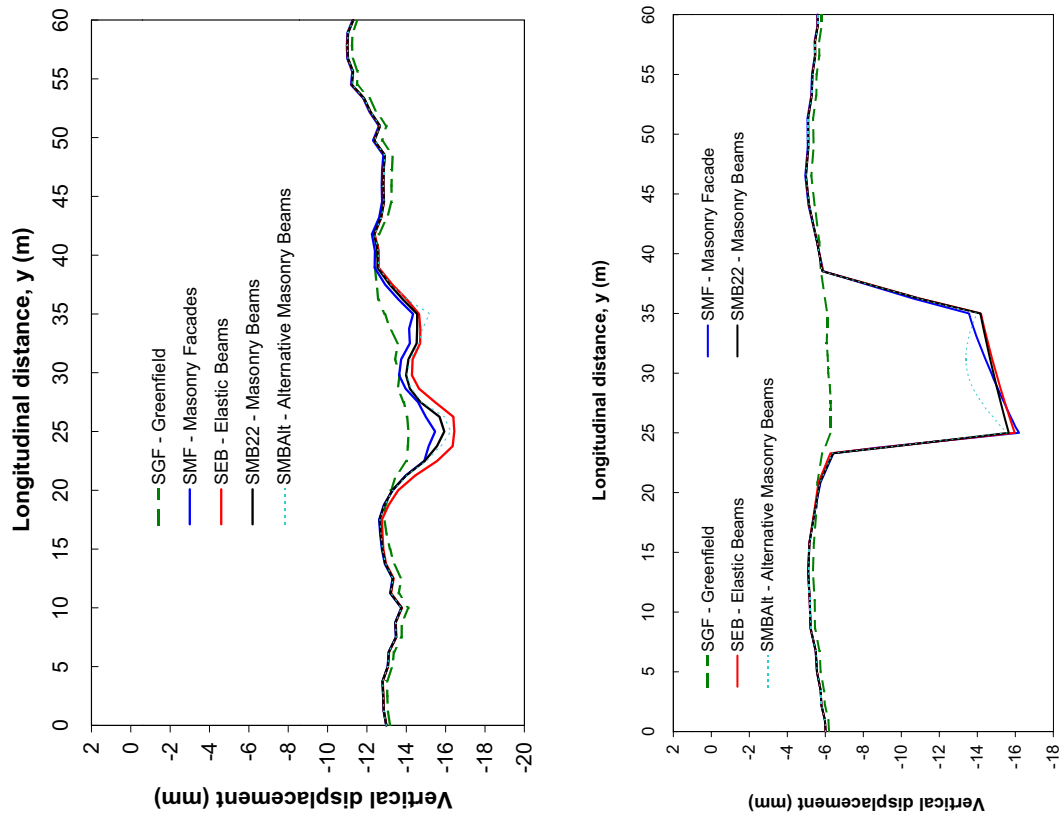
8.2.6 Summary

There are a number of items of note arising from the symmetric analyses of building response to tunnelling. The surface profile for using equivalent elastic surface beams is very similar to the profile under a full masonry facade. This indicates that the Timoshenko beam elements with equivalent elastic beam properties based on the geometric method developed in this thesis, are successful for facades in sagging. Altering the in-plane bending stiffness of the elastic beams impacts the settlement profile in a similar manner to previously published investigations (Potts and Addenbrooke (1997), and Jenck and Dias (2004)).



(a) Transverse $y=25$ m

(b) Transverse $y=35$ m



(c) Longitudinal tunnel centre line $x=0$ m

(d) Longitudinal end wall $x=10$ m

Figure 8.24: Symmetric analyses: Comparison of numerical models