Numerical study of a measure for mitigating ground displacements induced by tunnelling

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ABSTRACT: The purpose of this paper is to present the results of a numerical study on the effects of a diaphragm wall embedded between a shallow tunnel and a structure exposed to potential damage.

Numerical analyses were carried out by the code PLAXIS©: the tunnel was modelled as an unlined 8 m diameter circular cavity with a cover varying in the range C/D = 1 ÷ 2. A diaphragm wall close to the tunnel was also modelled, by using beam elements. Its geometry was changed: the main geometrical factors (wall length and thickness), the roughness of the interface between the soil and the wall, the wall self weight and its offset from the tunnel axis were combined in a number of cases and the results in terms of horizontal and vertical displacements at surface and in depth were investigated. A different ability of modifying in a favourable way the greenfield displacement field was observed, depending on the combination of factors, and a different sensibility to the variation of each factor was highlighted.

1 INTRODUCTION

In the industrialised world there is a growing need to improve public transport systems in densely populated urban areas. A commonly adopted strategy for making these improvements is to construct underground networks, which minimise the environmental impact of the transportation system. However the construction of tunnels and deep excavations for new metro systems, often at relatively shallow depths, has the potential to cause significant damage to existing buildings and services as a result of ground movements caused by soil excavation.

The underground construction of large diameter tunnels at a very shallow depth is considerable risk to historic buildings. Therefore, an issue of concern for designers is often the need of mitigating the effects of ground movements caused by underground excavations. This can be achieved by using a variety of different techniques for ground movement control. Among other protecting measures (Harris, 2001) it seemed to be possible the use of ground reinforcement to reduce the damage to buildings by introducing in the soil elements acting like a barrier which modifies the displacement fields. A few actions of this type were undertaken in some similar cases and are detailed in recent published works (Chen *et al.*, 1998; Sola *et al.*, 2003; Oteo *et al.*, 1999).

In many cases, different solutions for similar problems are adopted in practice, on the basis of some empirical knowledge of their effects, much more than following a rational design process. This is largely due to the lack of field measurements and to the low research effort of modelling the effects of the most common protective actions. At the origin of this paper was therefore the intent to investigate the influence of several parameters on the behaviour of vertical diaphragm walls embedded between the tunnel and the ground area to be protected.

2 DESCRIPTION OF THE NUMERICAL MODEL

Plane strain numerical analyses were performed by the commercial numerical code PLAXIS©.

The mesh of linear strain 6-node triangles is 168 m wide and 64 m deep. The tunnel has a 8 m diameter, its axis being 12 m or 20 m deep (C/D = 1 and 2, respectively). The mesh sides are restrained from moving horizontally and free to settle, the bottom is restraint in both horizontal and vertical displacements. The ground water level is at the ground level.

The tunnel excavation is simulated by eliminating the corresponding elements and by substituting them with a system of stresses of the same entity and opposite sign of those exerted by the elements of the tunnel on its geometric contour. Each analysis has been subdivided in subsequent phases, associated to different percentages of stresses reduction. The excavation is continued up to failure. The numerical analyses are performed in effective stresses and undrained conditions. This choice was adopted in order to simplify the comparison of greenfield calculated settlement profiles with those from empirical methods. Nevertheless, some sample calculations have shown that the main conclusions of the study also apply to drained conditions.

The soil is modelled as Hardening Soil, a nonlinear elastic-plastic constitutive model with volumetric and deviatoric hardening, implemented in the code (Schanz *et al.*, 1999) and the values of the adopted mechanical parameters are typical of a soft soil (Tab.1).

A first reference analysis has been carried out without diaphragm wall, in order to obtain settlement troughs at different stress reduction levels.

A series of analyses has been carried out with an elastic diaphragm wall ($E = 70$ GPa, $\nu = 0.25$) at a side of the tunnel. A sketch of the model is shown in Figure 1.

The wall length L, its distance from the tunnel axis d, its thickness t, its weight and the relative roughness of the interface were varied, as shown in Table 2.

Table 1. Soil parameters for Hardening Soil.

Parameter	Value	
γ	17.5	kN/m^3
$E_{50,ref}$ (per pref = 100 kPa)	8000	kN/m^2
$E_{ur,ref}$ (per pref = 100 kPa)	24000	kN/m^2
$E_{oed,ref}$ (per pref = 100 kPa)	9000	kN/m^2
Cohesion c	0.001	kN/m^2
Friction angle ϕ	22.8	°
Dilatancy angle Ψ	0	°
Poisson's ratio ν_{ur}	0.2	–
Power m	1	–
Tensile strength	0	kN/m^2
Failure ratio q_{fail}/q_{asy}	0.9	–

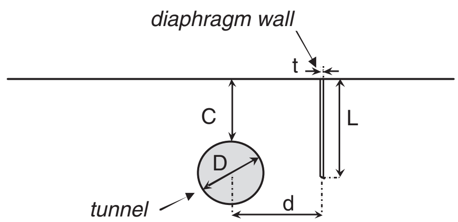

Figure 1. Sketch of the model.

Table 2. Wall geometrical parameters.

C/D	L	d	t (m)	Weight (kN/m3)	Interface
1	1 ÷ 4.5D	D	0.1 (stiff)	17.5 (light)	Rough
2	1 ÷ 4.5D	1.5 D	0.12 (flexible)	27 (heavy)	Smooth

The parameter R is used in the code as a strength reduction factor for the interface: R = 1 was used to model rough walls, R = 0.1 to model slip walls.

The effects of installation of the diaphragm wall were not considered.

3 RESULTS OF THE ANALYSES

In Figure 2 a normalised reference settlement profile is compared to a normalised Gaussian curve: the agreement between the two normalised troughs is possible, hence the FEA profile is in fact a Gaussian distribution of settlement. Nevertheless, the width of the settlement trough i, which allows such a distribution is about 9.5 m: this value correspond to a ratio $K = i/(C + D/2) = 0.79$, which is much higher than the empirical values usually adopted for such soils (O'Reilly & New, 1982). This is a common shortcoming of numerical predictions when isotropic elasticity is used to model the reversible strains in tunnelling processes (Addenbrooke *et al.*, 1997).

The computed settlement trough when no diaphragm wall was embedded in the numerical model has been used as a reference profile (indicated as 'no wall' in the charts) for comparison with homologous settlement profiles with embedded diaphragm walls. The influence of varying the variables shown in Table 2 will be next commented by using the surface settlement profiles from several numerical analyses, corresponding to a supporting stress distribution around the tunnel boundary which determined a settlement trough area equal to 1% of the tunnel area. As undrained conditions were imposed, this computed value corresponds to a so called 'volume loss', as it is usually defined in practice.

In Figure 3 the influence of varying the wall length is shown. The settlement troughs refer to numerical models with tunnel depth and wall characteristics as shown in the left side of the figure.

The wall can be concisely defined as a rough, stiff and heavy wall, in the sense of Table 2. The wall

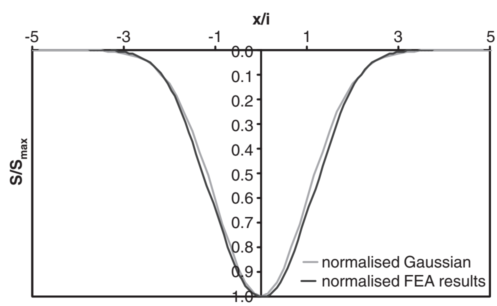

Figure 2. Comparison between empirical and FEA normalised settlement profiles.

length has been varied by deepening the wall from the tunnel crown (L = C) up to 1.5 D below the tunnel invert (L = 3.5 C).

The main effect of the wall is of reducing the settlement beyond its location. This happens as soon as the wall length overcomes a certain value and a clear effectiveness of such a wall in reducing settlement can be observed once the wall is deepened between 2 and 2.5 C, that is below the tunnel invert. A further effect of this kind of walls seems to shift the maximum settlements on the opposite side of the tunnel.

In Figure 4 settlement profiles referred to analyses with walls similar in all to the previous ones but sensibly lighter are shown. The wall unit self weight has been deliberately chosen equal to the soil's in order to avoid the influence of the extra-weight. The overall behaviour of such light walls is similar to that of the heavy ones, but it seems worth noticing some differences. The effect of weight can be observed by comparing in Figures 3 and 4 the profiles corresponding to L = C: by introducing a very short wall without increasing weight (Fig. 4) the settlement profile does not vary, except for the local influence of the wall stiffness at the wall location; on the other hand, the same wall with an higher self weight than the removed soil slightly increase the settlements and 'attracts' the settlement trough to its side (Fig. 3).

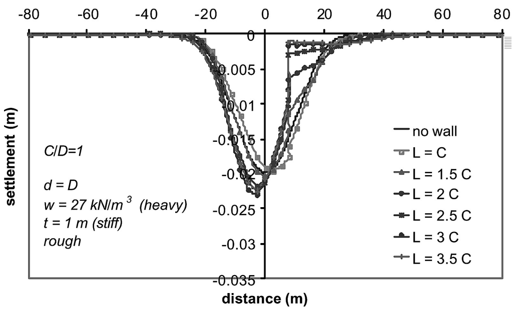

Figure 3. Comparison of settlement profiles: rough, stiff and heavy walls of various lengths.

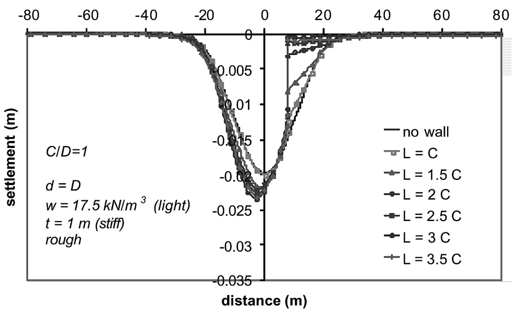

Figure 4. Comparison of settlement profiles: rough, stiff and light walls of various lengths.

The effect of the wall self weight is therefore of increasing the settlements when the diaphragm wall is not well founded below a certain level and at a certain distance from the tunnel. This has been also observed and discussed by physical modelling and numerical analyses with a different constitutive law (Bilotta, 2004). By comparing Figure 3 with Figure 4 it can be further observed that light walls start to be effective at a shorter depth than the heavier ones, that is between 1.5 C and 2 C. Moreover, the effectiveness of light walls in reducing settlements is higher than for heavier. In both cases, it can also be observed that by increasing the wall length over a certain level (i.e. from 3 C to 3.5 C) the beneficial effect does not increase more.

A comparison of the effects of diaphragm walls having the same characteristics as in Figure 3 but a very smooth interface (i.e. 'smooth, stiff and heavy walls') can be done by looking at Figure 5.

Differently from what happens with rough walls, the presence of a smooth wall causes an evident discontinuity in the settlement profiles between the two sides of the wall. This is already clear in the settlement profile for L = C, but the effectiveness of the smooth wall in reducing settlement beyond its location starts for L = 1.5 C. For a length equal to 2 C the reduction of settlement beyond the smooth wall is similar to that of a rough wall 2.5 C long. Moreover, further increase of length leads the wall to counter-rotate thus inducing a slight heave at its back.

The effects of more flexible walls can be observed in Figure 6. The 'screen' effect of the flexible diaphragm walls does not differ particularly from that of the corresponding stiff wall, a part in the vicinity of the wall, where the settlement profile tends to be closer to the reference profile without wall. The range of wall flexural rigidity between the two sets of analyses is quite wide (the 'stiff' wall is over 500 times stiffer than the 'flexible' one), therefore it should be concluded that the wall stiffness is not a major factor in such a problem.

In Figure 7 the settlement profiles of model with walls of the same length and different characteristics

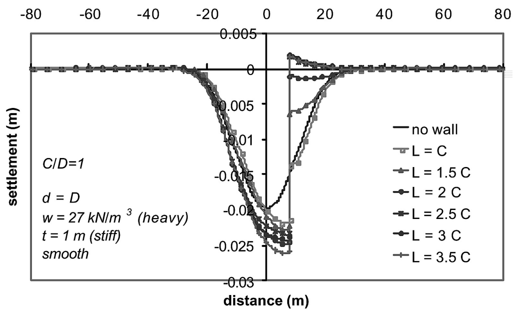

Figure 5. Comparison of settlement profiles: smooth, stiff and heavy walls of various lengths.

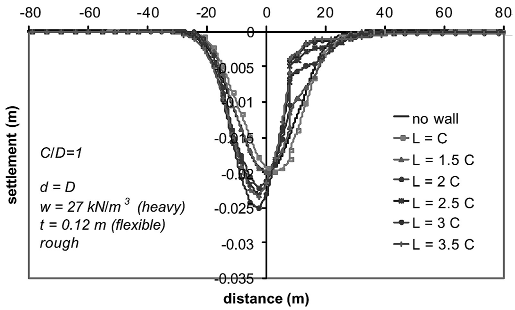

Figure 6. Comparison of settlement profiles: rough, flexible and heavy walls of various lengths.

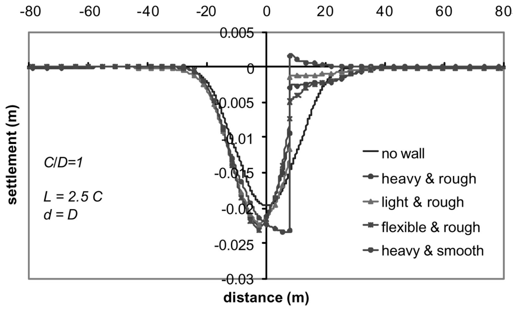

Figure 7. Comparison of settlement profiles: different kind of walls of the same length.

are compared. The profiles are labelled following the usual terminology (*cf* Tab. 2). It has been chosen to compare the profiles for a wall length L = 2.5 C as for this value the wall appeared to be effective in reducing settlements in all the set of analyses above discussed.

The settlement trough in Figure 7 show clearly and quickly that a diaphragm wall of a reasonable length, located 1 D away from the tunnel axis is able to reduce settlements beyond its location, that is in the ground area to be protected. Its effectiveness is strongly dependent on the wall interface characteristics and also on the wall extra-weight, whereas the wall flexibility is a less important factor.

Moreover the location of the wall seems not to affect the magnitude of settlements beyond the wall location, as it can be observed by looking at the settlement profiles in Figure 8.

The 'screen' effect of the diaphragm wall can be also observed in Figure 9.

In the figure, the shear stresses at collapse in two analyses (rough, heavy and stiff walls, L = C and 2.5 C) are plotted over the mesh as fractions of the failure shear stress. It can be observed that whereas for L = C the wall is completely immersed in the portion of ground which fails, for L = 2.5 C a substantial portion of the wall is in a 'stable' soil and the ground beyond the wall is screened from the collapsing area.

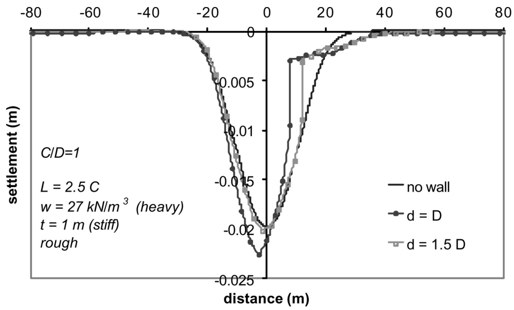

Figure 8. Comparison of settlement profiles: same wall at two different location (D and 1.5 D away from the tunnel axis).

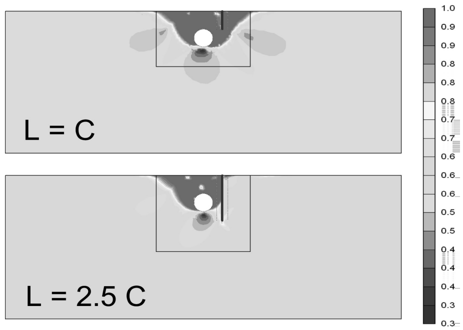

Figure 9. Relative shear stress filled contours at collapse.

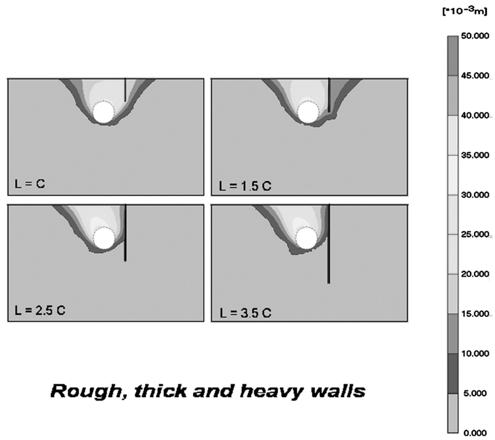

Figure 10. Displacement filled contours at V' = 1% – rough walls.

In other words, the wall acts as an element which modifies the shear stress transmission between the tunnel and ground area to be protected.

This effect is enhanced when the interface between the wall and the soil is smooth. This can be observed by comparing Figure 10 with Figure 11.

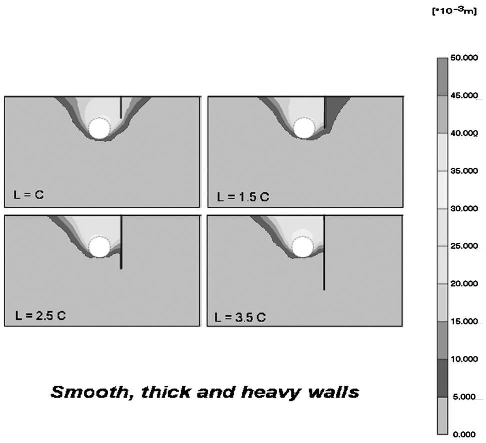

Figure 11. Displacement filled contours at V' = 1% – smooth walls.

In Figure 10, the displacement contours at V' = 1% are plotted for the analysed cases of rough, stiff and heavy walls of four different lengths. In Figure 11, the same displacement contours are plotted for the corresponding cases where the walls had a smooth interface.

The effect of increasing the wall length is different in the two cases. When a rough wall is embedded in the soil, by increasing its length the displacement fields around the tunnel cavity migrates on the opposite side of the wall, whereas it reduces at the wall back when a sufficient length has been achieved (Fig. 10). If the wall is smooth, it 'attracts' displacements in the area between itself and the tunnel, due to the smoothness of its interface with the surrounding soil. Moreover, it reduces almost to zero ground movements behind, for a shorter length than a rough one (Fig. 11). For L = C the wall is completely immersed in the portion of ground which experiences movements larger than 5 mm: both the rough and the smooth walls do not alter sensibly the overall displacement field. By increasing the wall length to L = 1.5 C, the influence of the wall on the displacement fields starts to be more evident and it can be noticed that the smooth interface enhances the 'screen' effect. In all, smooth walls appear again to be more effective as a barrier against ground movements induced by tunnel excavation.

4 EFFECTIVENESS OF THE PROTECTING MEASURE

In order to give a concise picture of the effectiveness of a vertical diaphragm wall as a barrier against tunnelling ground movements, an efficiency parameter can be defined (Bilotta, 2004) as follows:

$$\eta^{v} = \frac{S_{ref} - S_{bw}}{S_{ref}} \qquad (1)$$

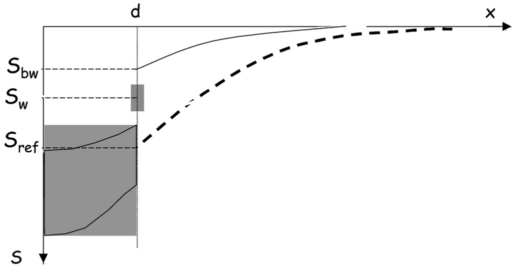

Figure 12. Definition of an efficiency parameter.

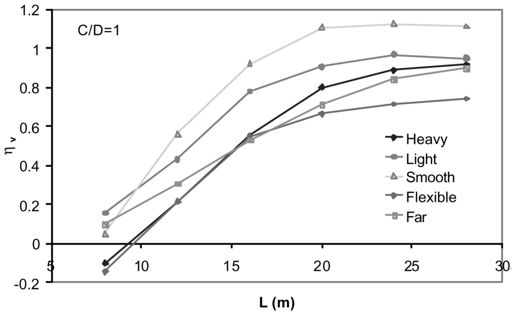

Figure 13. Efficiency of different kind of walls with length.

where the meaning of the variables is clarified in Figure 12: S_{ref} is the surface settlement in the no wall model at a distance d from the tunnel vertical centre line, S_{bw} is the settlement of the ground surface immediately beyond the wall (away from the tunnel).

When $\eta^{v} = 1$, the embedded diaphragm wall is completely effective to reduce settlement at its back, when $\eta^{v} = 0$ the wall has no influence at all on settlement. In some analyses it has been observed that the settlements behind the wall were higher than the reference settlements. In this case it can be computed $\eta^{v} < 1$, which means that the wall effect is undesirable as it does not achieve the goal it has been designed for.

The efficiency parameter varies with the wall length, as it is shown in Figure 13 for different set of wall characteristics (*cf* Tab. 2).

Smooth wall efficiency is always positive and reaches values of unity and more very easily, by increasing length: values higher than 1 indicate the small heave behind a smooth wall which has been observed in Figure 5. Light rough walls are also very soon effective, and in any case more effective than heavy rough walls, even if the difference decreases for deep embedment. The difference between stiff and flexible walls is zero up to a length, then it increases but, as observed in Figure 7 this appears rather be a local effect in the wall vicinity. Finally, if the rough, heavy and stiff wall is located 1.5 D away from the tunnel axis, that is slightly farther than in the other sets of analyses ('far' in the figure), its efficiency is

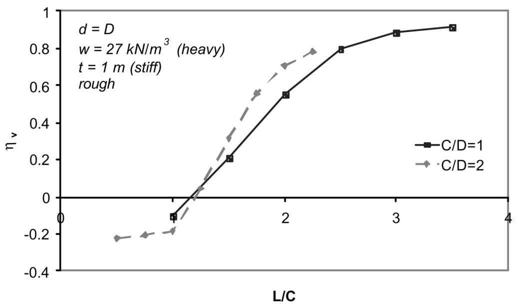

Figure 14. Efficiency of heavy, stiff and rough walls with L/C.

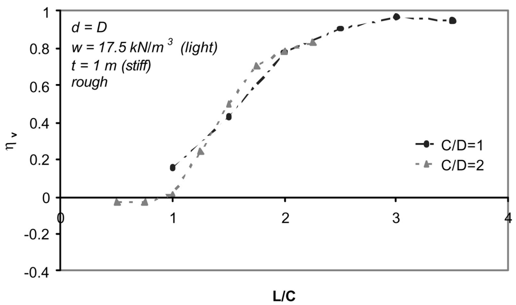

Figure 15. Efficiency of light, stiff and rough walls with L/C.

in average the same as for d = D, being slightly higher for low lengths and slightly lower for high lengths.

The influence of the tunnel cover on the wall effectiveness has been also investigated. In Figures 14 and 15, the efficiency of stiff and rough walls, heavy and light respectively, when the tunnel is under a cover C equal either to D or 2 D are plotted against a normalised length L/C.

The curves relevant to C/D = 1 and C/D = 2 are substantially superimposed in each of the two charts, thus allowing a limited generalisation of the previous observations to slightly deeper tunnels. It is worth noticing that whereas heavy walls need to be embedded about 1.5 D not to be negatively effective ($\eta^v < 1$), the efficiency of light walls is practically always not negative.

5 CONCLUDING REMARKS

The results of the numerical study described so far have shown the effectiveness of vertical diaphragm walls as a barrier to reduce ground movements in an area close to a shallow tunnel during the excavation.

A major attention in design should be paid to the wall length, even if its self-weight and the roughness of its interface with soil also have a strong influence on the tunnel-wall behaviour. In order to gain a sufficient efficiency, the wall should be deepened at least at the invert level, as it could be logically expected. The wall self weight should be reasonably contained, in order to increase the wall efficiency in reducing ground movements. Walls with a very smooth interface are able to introduce a strong discontinuity in shear stress transmission, which can be used to reduce ground movements in the area of interest. On the other hand, as far as the wall is vertical, the wall thickness does not influence very much its performance. Finally, the distance between the tunnel and the diaphragm wall does not affect the efficiency of the wall, at least within the values considered in this study. Since it is well known that the actual settlement through is narrower than that obtained by FEA, such a conclusion could be questionable.

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