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Deformations caused by the excavation of twin tunnels

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ABSTRACT: The use of the underground has been a growing solution found for the installation of infrastructure and (or) transport networks in the last decades. In these networks it is common to sequentially excavate tunnels in close proximity. Several case studies reported that the deformations associated with the excavation of a second tunnel were higher than those recorded in the first, showing that in this scenario there seems to have an interaction between tunnels. In order to predict the settlement profile induced by the excavation of the second tunnel several methods have been proposed based on numerical, centrifuge and small scale models. In this paper the results obtained with a numerical analysis of the excavation of two twin tunnels are presented and compared against those proposals. The results confirm that the presence of the first tunnel influences the excavation of the second tunnel. Based on a parametric study carried out it was possible to verify that interaction occurs regardless of the depth of the tunnel, though it is strongly dependent on the pillar width between tunnels.

1 INTRODUCTION

The excavation of tunnels inevitably induce movements in the surrounding soil. These are particularly relevant in the case of shallow tunnels, since the deformations extend to the ground surface and might cause severe damage in the structures or infrastructures located in the vicinity of the excavation. Consequently, the evaluation of the extent of the surface settlement trough and of the magnitude of the vertical and horizontal displacements caused by tunnelling is of paramount importance and must be properly addressed during the design stage.

The prediction of the ground movements caused by tunnelling has been widely investigated by several authors having the excavation of a single tunnel as main reference (Peck, 1969; O'Reilly & New, 1982; Mair & Taylor, 1997; Almeida e Sousa, 1998). However, and particularly in transport systems, it has become frequent to excavate sequentially side by side twin tunnels. In this scenario it has been found that the simple superposition of two single tunnel predictions is not adequate since the presence of the first tunnel affects the excavation of the second (Bartlett & Bubbers, 1970; Cording & Hansmire, 1975; Nyren, 1998; Withers, 2001; Cooper et al., 2002). The interaction between both tunnels is usually assessed through the inspection of the transverse settlement trough at ground surface, since this data is usually measured in real cases and can easily be interpreted. Figure 1a) was presented by Bartlett & Bubbers (1970) and shows the settlement trough caused by the excavation of twin tunnels in London Underground Victoria

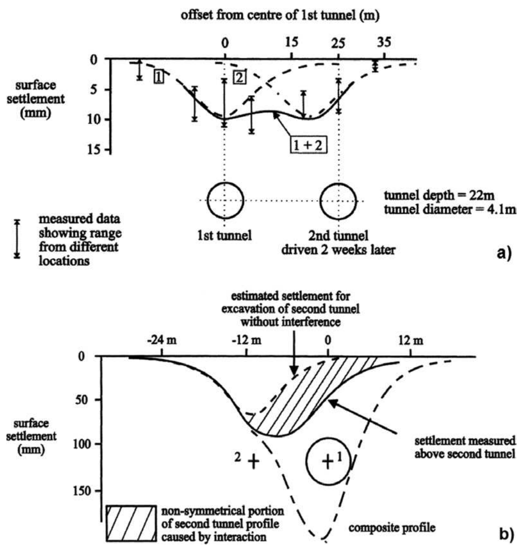

Figure 1. Settlements induced by the excavation of twin tunnels: a) Bartlett & Bubbers (1970); b) Cording & Hansmire (1975).

Line. Although the measured settlements can be adjusted by the superposition of two single tunnel predictions (1 plus 2), the parameters used in the fitting of both curves have to be different and the curve associated with the excavation of the second tunnel presents some eccentricity towards the first tunnel in order to reproduce the maximum settlement, which does not occur aligned with the centreline of the second tunnel. In the case of the Lafayette Park of the Washington Metro network, presented by Cording & Hansmire (1975) and depicted in Figure 1b), it was also possible to verify that beside the eccentricity of the maximum settlement towards the first tunnel a significant increase of the settlement trough volume occurred in comparison with the predicted if the excavation of the second tunnel was performed without interference.

Several other cases where a similar behaviour was observed due to the sequential excavation of side by side twin tunnels have been reported in literature (Peck, 1969; Cooper & Chapman, 1998; Nyren, 1998; Cooper et al., 2002; Ocak, 2014). Mair & Taylor (1997) stated that this asymmetric behaviour and the increase of volume loss mainly occurs when the tunnels are closely spaced, since in this case the soil around the first tunnel is already disturbed and with reduced stiffness due to the excavation. Naturally, the construction of the second tunnel in these ground conditions will induce higher displacements and an eccentricity of the maximum displacement towards the first tunnel, where the soil is more disturbed.

These conclusions are supported by the results of numerical (Addenbrooke & Potts, 2001; Hunt, 2005), centrifuge (Divall, 2013) and small scale (Chapman et al., 2006) models. Regardless of the type of study all concluded that the principal aspect responsible for the interaction of side-by-side twin tunnels was the pillar width, *L*, between tunnels. Based on the results of those studies new methods for predicting the deformations induced by the excavation of a second twin tunnel were proposed.

In this paper a numerical study of a twin tunnel excavation was performed with the purpose of verifying the validity of the proposed methods. Additionally, the results of a parametric study carried out in order to evaluate the influence of that factors, such as the depth of the tunnel and the pillar width between tunnels, have in the resulting deformations are presented.

2 ESTIMATION OF TWIN TUNNEL DEFORMATIONS

2.1 *Surface settlements*

It is commonly accepted that for greenfield conditions the surface settlement trough caused by a single tunnel excavation can be reasonably fitted by a Gaussian curve as suggested by Peck (1969). The prediction of the vertical settlement at any point of the ground surface $\left(\delta_v(x)\right)$ can then be determined using Equation 1, where $\delta_{v\,max}$ is maximum vertical settlement at the tunnel centreline and *i* is the trough width parameter. The value of $\delta_{v\,max}$ can be related with the volume loss, V_L, (expressed as a ratio of the area of lost ground to the area of the excavated tunnel) and with the diameter, *D*, of the tunnel through Equation 2. The trough width parameter is usually expressed as a direct function of a constant, *K*, and of the depth of the tunnel axis level, Z_0 (Eq. 3). Typical values of these parameters for different soil conditions can be found in Mair & Taylor (1997) and Hunt (2005).

$$\delta_v(x) = \delta_{v\,max} \cdot \left[e^{\left(-\frac{x^2}{2 \cdot i^2}\right)} \right] \qquad (1)$$

$$\delta_{v,max} = \sqrt{\frac{\pi}{32}} \cdot \frac{V_L \cdot D^2}{i} \qquad (2)$$

$$i = K \cdot Z_0 \qquad (3)$$

A first prediction for the twin tunnel scenario, where both tunnels are side-by-side at the same depth, was proposed by New & O'Reilly (1991) and assumed that the final settlement trough could be given by the direct superposition of two single Gaussian curves (Eq. 4), spaced of the distance between the centrelines of the tunnels, *d*.

$$\delta_v(x) = \delta_{v\,max} \cdot \left[e^{\left(-\frac{x^2}{2 \cdot i^2}\right)} + e^{\left(-\frac{(x-d)^2}{2 \cdot i^2}\right)} \right] \qquad (4)$$

However, this proposal does not account for any interaction effects that might occur during the excavation of the second tunnel, since $\delta_{v\,max}$ and *i* are considered equal for each tunnel. This assumption is not in agreement with the results of several case studies and therefore this proposal is only considered valid when the tunnels are reasonably spaced apart.

Based on a numerical study Addenbrooke & Potts (2001) proposed a new method for predicting the settlements associated with the excavation of the second tunnel (Tunnel B). The method consisted in the introduction of a correction to both the volume loss and the eccentricity of the second tunnel having as reference the result of a greenfield analysis. For that purpose the design charts presented in Figure 2 were proposed. The figure shows that the difference in terms of volume loss tends to decrease with the proximity of the tunnels, although even for an *L*/*D* ratio of 7 a 10% increase is expected. The eccentricity also follows a similar behaviour, though a limit of 0.5*L* is observed for *L*/*D* ratios below 2, meaning that for this ratio the maximum displacement is located at an equal distance of the two tunnels. After taking into consideration these two modifications the settlement trough of the second

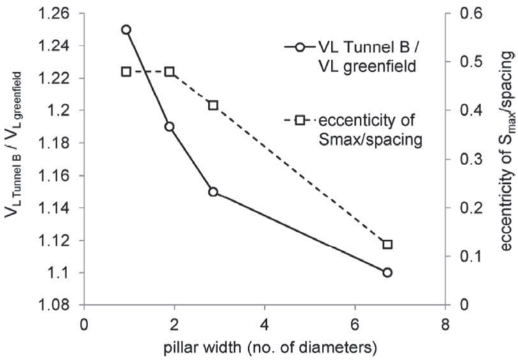

Figure 2. Addenbrooke & Potts (2001) proposal for determine the volume loss (left) and eccentricity of the maximum settlement (right) of the second tunnel excavated (Tunnel B).

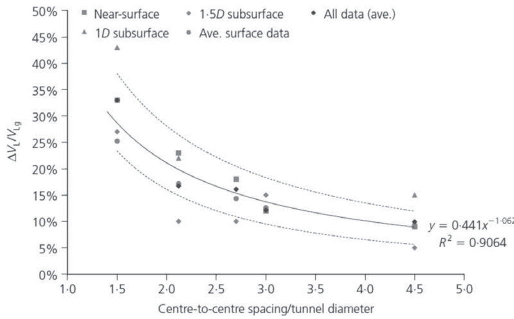

Figure 3. Increases in the second tunnel volume loss in comparison with first tunnel (after Divall (2013)).

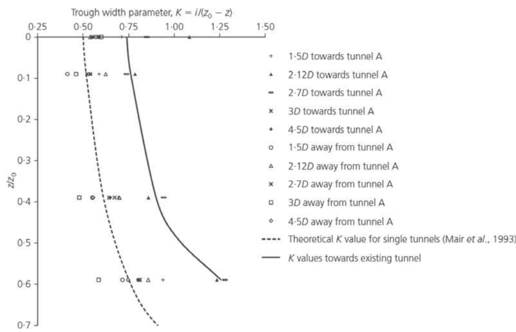

Figure 4. Variation of K values plotted with depth (after Divall (2013)).

tunnel can be determined and the final displacement profile can be obtained by superposition of the amended curve with the one predicted for the first tunnel, excavated in greenfield conditions.

Hunt (2005) based on a numerical study and supported by small scale models proposed a new methodology for amending the settlement trough of the second tunnel. This method consists on the application of a correction factor to Equation 1 as shown in Equation 5. However, this correction must only be applied in the overlapping zone between the two tunnels, which is considered the zone disturbed by the excavation of the first tunnel. The parameters M and A of the equation were adjusted numerically and, according to Hunt (2005), can be considered in the range of 0.6 to 0.8 and of 2.5 to 3.0, respectively. This correction is maximum above the centreline of the first tunnel, typically about a 1.6 to 1.8 increase, and should not be considered less than unity. Just like in the previous method the final settlement trough can be obtained by superposition of the modified second tunnel curve with the one estimated for greenfield conditions for the first tunnel.

$$\delta_v(x) = \delta_{v\,max} \cdot \left[e^{\left(-\frac{x^2}{2 \cdot i^2}\right)} \right] \cdot \left[1 + \left(M \cdot \left(1 - \frac{d+x}{A \cdot i} \right) \right) \right] \quad (5)$$

A third method was proposed by Divall (2013) based on results of centrifuge tests carried out at City University of London. This methodology is similar to that presented by Addenbrooke & Potts (2001), with design charts being proposed for the correction of the second tunnel volume loss (Figure 3) and for the trough width constant *K* (Figure 4). Also in this case the volume loss of the second tunnel is increased in comparison to the greenfield prediction. The corrected volume loss can then be used in Equation 2 to determine the maximum vertical displacement of the tunnel assuming a trough width parameter calculated using Equation 3, with *K* being estimated using the dashed curve for single tunnels in Figure 4. However, in order to determine the settlement trough profile (Eq. 1) it is suggested to use distinct values of *i* depending on the side of the curve. For the side towards the existing tunnel a higher value of *K* is proposed in order to reflect the interaction with the existing tunnel. According to Figure 4 a value of 0.75 can be adopted at ground surface (solid line). As for the side away from the existing tunnel a value of $K = 0.5$ can be assumed. Also in this case the final settlement profile is given by the sum of the modified settlement trough of the second tunnel with that obtained in greenfield conditions for the first tunnel.

More recently, Ocak (2014) proposed Equation 6 to determine the final settlement trough induced by twin tunnel excavation. This expression, based on the observations of the Istanbul Metro Line, considers that the interaction between tunnels can be reproduced by simply adding a so-called disturbance factor into Equation 4.

According to the author, this disturbance factor is a function of the diameter of the tunnel, D, and of the distance between centrelines of the tunnels, d. This method considers that both Gauss curve parameters, $\delta_{v\,max}$ and i, are equal for both tunnels.

$$\delta_v(x) = \delta_{v\,max} \cdot \left[e^{\left(-\frac{x^2}{2\cdot i^2}\right)} + \left(1 + \frac{D}{d}\right) \cdot e^{\left(-\frac{(x-d)^2}{2\cdot i^2}\right)} \right] \tag{6}$$

2.2 *Sub-surface vertical displacements*

Since most of the foundations of the buildings and infrastructures are not located at ground surface it is also important to predict the sub-surface displacements induced by tunnelling. However, in this case there are not many methodologies available to predict these movements in a twin tunnel scenario.

Mair et al. (1993) based on the analyses of several case studies and on the results of centrifuge tests verified that the sub-surface vertical deformation troughs could also be approximated by a Gauss curve. However, they observe that the trough width constant, K, varied with depth, z, and proposed Equation 7 to account for that aspect.

$$K = \frac{0.175 + 0.325 \cdot \left(1 - \frac{z}{Z_0}\right)}{1 - \frac{z}{Z_0}} \tag{7}$$

Using the K value the vertical displacement trough at a given depth z could simply be estimated by employing Equation 8, which is very similar to Equation 1, with the only change being the introduction of the depth factor.

$$\delta_v(x) = \delta_{v\,max} \left[e^{\left(-\frac{x^2}{2K^2(Z_0-z)^2}\right)} \right] \tag{8}$$

However, this expression was derived for the case of a single tunnel excavation and does not account for the interaction effects observed in the twin tunnel scenario. To include those Hunt (2005) proposed Equation 9, which amends the sub-surface displacements by the same correction factor he derived for the ground surface settlement troughs. This equation can be used to predict the sub-surface displacements induced by the excavation of a second tunnel and its results should be summed with those of the unchanged first tunnel to obtain the final vertical sub-surface displacement trough.

$$\delta_v(x) = \delta_{v\,max} \left[e^{\left(-\frac{x^2}{2K^2(Z_0-z)^2}\right)} \right] \left[1 + \left(M \left(1 - \frac{d+x}{AK(Z_0 - z)} \right) \right) \right] \tag{9}$$

Divall (2013) also suggests the use of Equation 8 to predict the sub-surface vertical displacements. However, he proposes the correction of the volume loss of the second tunnel according to Figure 3 and of the constant K using Figure 4. Also in this case the constant K should differ depending if the curve is towards or away from the existing tunnel.

2.3 *Horizontal displacements*

The estimation of ground surface horizontal displacements is more complex since the data available for interpretation is limited. For that reason it is often considered that these displacements are related with the vertical settlements and can be estimated assuming that the vectors of ground movement are directed towards the tunnel axis. Based on this assumption O'Reilly & New (1982) proposed Equation 10 to estimate the horizontal ground surface displacements caused by the excavation of a single tunnel. In order to include the interaction effects of a second tunnel excavation Hunt (2005) proposed the introduction of a correction factor (Eq. 11), equal to that suggested for the surface settlements, but that should only be applied to the side of the curve towards the excavation of the first tunnel.

$$\delta_h(x) = \delta_v(\mathrm{x}) \cdot \frac{x}{Z_0} \tag{10}$$

$$\delta_h(x) = \delta_v(\mathrm{x}) \cdot \frac{x}{Z_0} \cdot \left[1 + \left(M \cdot \left(1 - \frac{d+x}{A \cdot i} \right) \right) \right] \tag{11}$$

3 NUMERICAL MODEL

The numerical analyses were performed using the finite element program developed at the Department of Civil Engineering of the University of Coimbra, UCGeoCode. A 2D numerical model assuming plane strain conditions was elaborated in order to evaluate the influence of the excavation of twin tunnels. The geometry of the reference model is presented in Figure 5 and has dimensions of 154 m x 36 m. Two circular tunnels with a diameter, D, of 8 m were located initially at a depth, Z_0, of 12 m (cover of 8 m) and centred in the mesh. The reference distance between centrelines, d, is of 10 m, which corresponds to a pillar width, L, of just 2 m. Different values for the depth of the tunnels and for the pillar width were considered in other models in order to evaluate their influence.

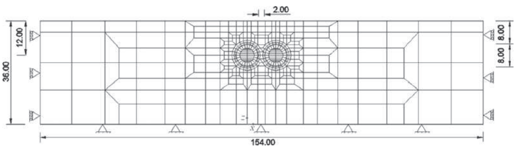

Figure 5. Reference finite element mesh.

The boundary conditions were defined so that no horizontal displacements were possible along the vertical boundaries. In the bottom boundary no movements were allowed in any direction, while at the top no restriction was considered and free movements were possible in both directions.

The lining of both tunnels was simulated using 0.3 m thick solid elements modelled as a linear elastic material, with a Poisson's ratio of 0.2 and a Young's modulus of 20 GPa. For the soil a conventional Mohr-Coulomb failure criterion was adopted with an angle of shear resistance of 35º, a cohesion of 10 kPa and an angle of dilation of 5º. For the stiffness a constant Poisson's ratio of 0.3 was assumed. The deformability modulus, E, was also considered constant throughout the analysis, although its value varied in depth with the initial confining stress, σ_{30}, according to the Janbu (1967) law (Equation 12). For the atmospheric pressure, P_a, a value of 100 kPa was assumed while 200 and 0.5 were the values adopted for the parameters A and n, respectively.

$$E = A \cdot P_a \cdot \left(\frac{\sigma_{30}}{P_a} \right)^n \tag{12}$$

The initial stress state was considered to be geostatic and defined considering dry conditions, a unit weight of 20 kN/m^3 and an earth pressure coefficient of 0.5.

The tunnels were excavated in full section and in order to reproduce the 3D effects associated with the excavation of tunnels in 2D models the stress relaxation method was employed (Potts & Zdravković, 2001), with a stress relief value of 0.6 being applied in all the excavation stages. A total of 4 stages were modelled: 1) excavation of the left tunnel; 2) installation of its lining (1st T); 3) excavation of the right tunnel; and 4) installation of its lining (2nd T).

4 REFERENCE ANALYSIS

4.1 *Surface settlements*

The results of the settlement troughs obtained in the reference analysis are plotted in Figure 6.

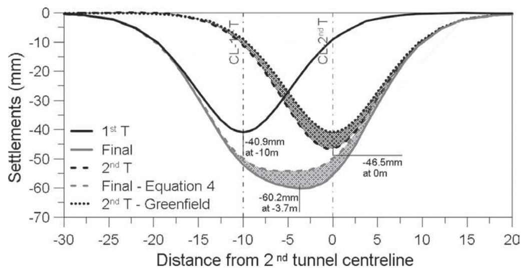

Figure 6. Settlement troughs obtained in the reference analysis.

Table 1. Parameters of the fitted Gauss curves.

Tunnel	$\delta_{v\,max}$	i	K	R^2
1st T	–40.4	5.75	0.48	0.99
2nd T	–46.0	5.79	0.48	0.99

Table 2. Volume loss of the settlement troughs (%).

1st T	Final	2nd T	Final – Eq. 4	2nd T – Greenfield
1.20	2.56	1.36	2.40	1.20

As expected the settlements associated with the excavation of the 1st Tunnel can be fitted almost perfectly to a Gauss curve (Table 1) centred in its centreline and with a maximum value of 40.9 mm. Naturally, with the excavation of the 2nd Tunnel, the settlements increase considerably reaching a maximum of 60.2 mm. An even higher increase was observed in terms of volume loss (determined using the trapezoidal rule), with a final value of 2.56% being determined against the 1.20% induced by the excavation of the 1st Tunnel (Table 2). However, the most noticeable result concerns the position of the final maximum settlement, which is not aligned with the 2nd Tunnel centreline, being shifted −3.7 m towards the 1st Tunnel. This result confirm the behaviour observed in several case studies that exhibit a similar eccentricity pattern (Bartlett & Bubbers, 1970; Cording & Hansmire, 1975). By subtracting the final settlements to those associated with the excavation of the 1st Tunnel it is possible to determine the settlements induced solely by the 2nd Tunnel. These can also be described by a Gauss curve centred above its centreline (Table 1), but reveal a maximum displacement value higher and also an increase in terms of volume loss (shaded dark area) of about 13% in comparison with the greenfield conditions (2nd T—Greenfield). In terms of the final settlement trough an increase of 6.5% (light shaded area) is obtained when compared against the New & O'Reilly (1991) proposal (Final – Equation 4). These results confirm that the presence of the 1st Tunnel affects the excavation of the 2nd Tunnel, both in terms of volume loss and eccentricity (ec). From the analysis of Table 1 it is also possible to observe that the difference between the Gauss curves adjusted to the settlements of both tunnels is essentially due to the maximum settlement value since the trough width parameter is approximately the same for both tunnels.

The final settlement troughs predicted by all methods are plotted in Figure 7 alongside the results from the reference analysis (REF). The principal results obtained are summarised in Table 3. It is possible to observe that all methods estimate maximum settlements and volume losses higher than those obtained in the REF analysis. Overall, the best approximation is given by Hunt (2005) proposal followed by Divall (2013) method. The settlement troughs estimated according to Addenbrooke & Potts (2001) and Ocak (2014) methodologies produce significant discrepancies. In these cases not just the maximum settlement value and volume loss is significantly overestimated, but also the settlement trough is substantially shifted towards the 1st Tunnel in the case of Addenbrooke & Potts (2001) and in the opposite direction, i.e. close to the 2nd Tunnel, in the case of Ocak (2014). The method that better predicts the eccentricity is, again, that proposed by Hunt (2005), although in this case a reasonable difference with the result of the REF analysis still occurs.

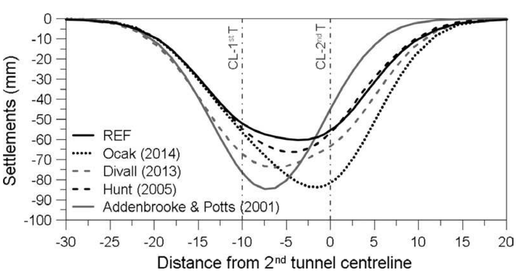

Figure 7. Final settlement troughs estimated by the proposed methods.

Table 3. Principal results of the settlement troughs determined by the proposed methods.

Result	REF	Addenbrooke & Potts (2001)	Hunt (2005)	Divall (2013)	Ocak (2014)
$\delta_{v\,max}$ (mm)	−60.2	−84.6	−66.2	−73.9	−80.8
e_c (m)	−3.7	−7.5	−5.0	−6.3	−1.4
V_L (%)	1.20	2.67	2.60	3.09	3.26

The discrepancies observed might be related to several aspects since the empirical methods were deduced based on specific conditions, such as the depth of the tunnel, the initial stress state, the soil properties among others, which were not exactly equal to those considered in the numerical analysis.

4.2 *Sub-surface vertical displacements*

The sub-surface vertical displacement at 4 and 6 m of depth are plotted in Figure 8 alongside the results obtained for the ground surface. From the figure it is possible to observe that the displacements tend to increase slightly with depth. It is also visible that the shape of the curve at 6 m depth presents two peaks, which are almost aligned with the centreline of each tunnel (Table 4). This result is due to the proximity of the 6 m depth profile to the crown of the tunnels, which is just 2 m below. The displacement difference observed in the two peaks, higher above the 2nd Tunnel, confirms that the presence of the 1st Tunnel affects the deformations induced by the second excavation also in depth. The results of the volume loss presented in Table 4 show that there is a slight increase in depth although the difference between the 2nd Tunnel and the greenfield scenario remains approximately equal to that observed at ground surface. However, it is interesting to note that the eccentricity of the maximum vertical displacement towards the

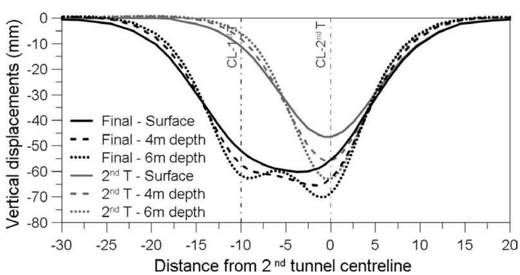

Figure 8. Final sub-surface vertical displacements at different depths.

Table 4. Principal results of the settlement troughs determined at different depths.

	1st Tunnel		Final		2nd Tunnel	
Result	–4 m	–6 m	–4 m	–6 m*	–4 m	–6 m
$\delta_{v\,max}$ (mm)	–49.2	–55.8	–65.5	–70.1 (–62.6)	–55.8	–63.1
e_c (m)	–10.0	–10.0	–1.4	–0.7 (–9.3)	0.0	0.0
V_L (%)	1.21	1.21	2.57	2.58	1.37	1.36

*values in brackets refer to the peak above the 1st Tunnel.

1st Tunnel tends to decrease with depth from –3.7 at ground surface to –0.7 at 6 m depth.

The comparison of the sub-surface vertical displacements of the reference analysis (REF) with the curves proposed by Hunt (2005) and Divall (2013) is depicted in Figure 9 for the depth of 6 m. The results show that the method proposed by Hunt (2005) has a good overall agreement with the numerical results, although it fails to predict the two peaks located above each tunnel. In contrast, the correction proposed by Divall (2013) tends to overestimate the displacements, particularly those above the 1st Tunnel, where the difference is considerable. This discrepancy is amplified by the use of a constant *K* higher towards the 1st Tunnel in the prediction of the 2nd Tunnel displacements.

4.3 *Horizontal displacements*

The results of the ground surface horizontal displacements (in absolute value) obtained in the reference analysis are displayed in Figure 10. As expected the results of the 1st Tunnel (greenfield conditions) are symmetrical relatively to the centreline of the tunnel. At this position the horizontal displacement is equal to zero and increases sharply up to 19.6 mm at a distance of 6.5 m (–16.5 m) from the centreline of the tunnel. For further distances the horizontal displacement decreases gradually towards zero.

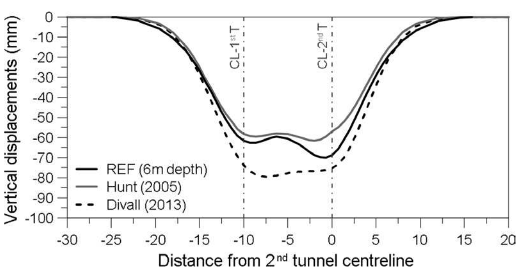

Figure 9. Final sub-surface vertical displacements at 6 m depth estimated by the proposed methods.

The final horizontal displacements present a similar behaviour although not symmetrical. From the figure it is possible to observe that the zero horizontal displacement occurs with an eccentricity of –3.7 m, which is equal to that observed for the maximum vertical settlement. The interaction effects between both tunnels are noticeable when comparing the maximum final horizontal displacements, with the side towards the 1st Tunnel presenting a higher value (29.2 mm) in comparison with the opposite side (28.1 mm). This difference becomes even clearer when the horizontal displacements associated with the excavation of the 2nd Tunnel are analysed (obtained by subtracting the 1st Tunnel horizontal displacements from the final displacements). The excavation of the 2nd Tunnel originates an increase of the displacements of approximately 21% on the side towards the 1st Tunnel, while in the opposite direction an increase of about 8% was found. These results show that the influence of the presence of the 1st Tunnel is even more relevant in the horizontal than in the vertical displacements.

The horizontal displacements predicted by the empirical methods for the 2nd Tunnel are displayed in Figure 11 alongside the results of the reference analysis and of the greenfield scenario (2nd Tunnel – Greenfield). The curves proposed by O'Reilly & New (1982) and Hunt (2005) predict considerably smaller horizontal displacements. However, they are able to predict successfully the overall trend and the position of the maximum values on both sides of the centreline. Naturally the method proposed by O'Reilly & New (1982) gives a symmetrical curve, with a maximum value of just 11,7 mm, since it does not account for any interaction between tunnels. In contrast the curve obtained using Hunt (2005) correction factor presents a significantly higher value (16.8 mm) on the side towards the 1st Tunnel, while in the opposite direction the result is similar to that predicted by O'Reilly & New (1982) equation, since no correction factor is applied.

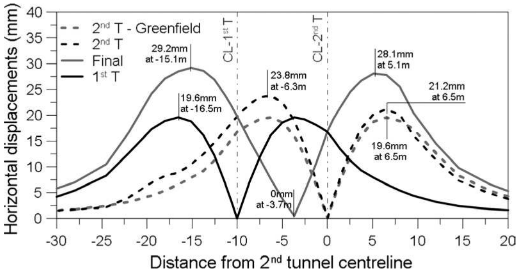

Figure 10. Horizontal displacements obtained for the reference analysis (absolute values).

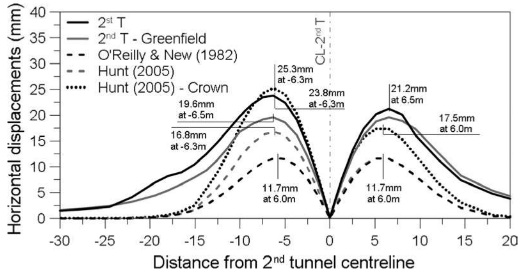

Figure 11. 2nd Tunnel horizontal displacements estimated by the proposed methods (absolute values).

A justification for the smaller predicted values is related to the assumption in both methods that the ground vector displacements are directed towards the tunnel axis. If instead the vectors were considered to be directed to the crown of the tunnel a better agreement would be achieved on both sides of the centreline using Hunt (2005) proposal as it is possible to observe in Figure 11 (Hunt (2005)—Crown).

5 INFLUENCE OF THE DEPTH OF THE TUNNEL

In order to evaluate the influence of the depth of the tunnels two additional analysis were performed. All parameters were kept unchanged and only the geometry of the model was modified to account for two scenarios. In the first (H = 20 m) the tunnels axes were located at 20 m depth while in the second (H = 28 m) a depth of 28 m was considered.

The results of the surface settlement troughs for the two analyses are plotted in Figure 12 alongside the reference case (REF), where a depth of 12 m was considered. The results show that an increase in the depth of the tunnels translates in a considerable increase of the volume loss of the settlement trough (Table 5). However, the maximum settlement show contradictory results, with the analysis where a tunnel depth of 20 m was considered presenting a smaller value than that obtained for the REF analysis, while the opposite occurs for the tunnel depth of 28 m. As for the eccentricity of the maximum settlement the results show that with the depth of the tunnel the curves tend to become centred in the middle point of the two tunnels, i.e., eccentricity equal to –5 m.

From the analysis of Figure 13, where the settlement due to the excavation of the 2nd Tunnel are depicted for the three analyses, it is possible to observe that the interaction effect (shaded areas) also occurs when the tunnels are located at higher depths. However, the results presented in Table 5 show that the increase of volume of the 2nd Tunnel appears to be almost independent of the depth of the tunnel, with an increase value of about 11%.

In Table 6 are summarised the principal results obtained with the different methods proposed for estimating the settlement trough. The results show that regardless of the depth of the tunnels all methods tend to overestimate the displacements. Also in this case the better adjustment is obtained using Hunt (2005) proposal followed by Addenbrooke & Potts (2001). The former is capable of predicting the eccentricity of the maximum displacements correctly while the latter presents the most approximate estimative of volume loss. The Divall (2013) and Ocak (2014) proposals exhibit the poorest predictions failing in predicting the volume loss by a considerable margin. Based on these results it is possible to conclude that overall the prediction of the different methods did not improve with the depth of the tunnel.

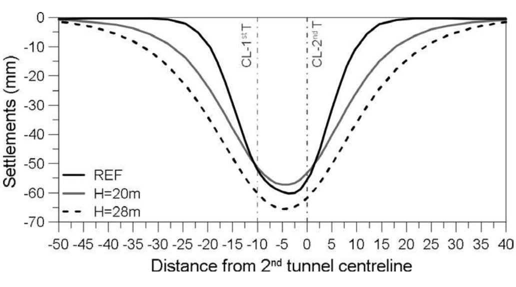

Figure 12. Influence of the depth of the tunnel on the settlement troughs.

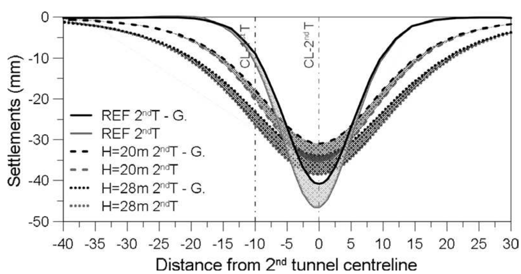

Figure 13. Settlement troughs induced by the excavation of the 2nd Tunnel for different depths.

Table 5. Volume loss of the settlement troughs (%).

Depth (m)	1st T	Final	2nd T	Final Equation 4	2nd T Greenfield
20	1.65	3.49	1.82	3.30	1.65
28	2.20	4.65	2.45	4.40	2.20

Table 6. Principal results of the final settlement troughs determined by the proposed methods for different depths of the tunnel (%).

Depth (m)	Result	REF	Addenbrooke & Potts (2001)	Hunt (2005)	Divall 2013)	Ocak (2014)
20	$\delta_{v\,max}$	−57.3	−67.6	−66.5	−65.2	−75.9
	e_c	−5.0	−7.5	−5.0	−6.3	−3.7
	V_L	3.49	3.54	3.56	3.99	4.29
28	$\delta_{v\,max}$	−65.5	−74.4	−76.4	−73.8	−86.0
	e_c	−5.0	−7.5	−5.0	−6.3	−3.7
	V_L	4.65	4.78	4.89	5.65	5.82

As for the final surface horizontal displacements the results plotted in Figure 14 show that the increase of the depth of the tunnels tends to decrease considerably the maximum values and that the displacements remain asymmetrical, with the side towards the 1st Tunnel showing higher values. It is also interesting to note that despite the differences all curves present a zero horizontal displacement at the same position, –3.7 m, measured from the 2nd Tunnel centreline. However, the position where the maximum horizontal displacements are located tend to shift away from the zero position with the depth of the tunnels, regardless of the side considered. For further distances a sharp decay of the horizontal displacements is observed in the reference analysis while for deeper tunnels it tends to be more gradual.

The prediction of the horizontal displacements associated with the excavation of the 2nd Tunnel using Hunt (2005) proposal and assuming that the vector of ground deformations is directed towards the crown of the tunnel is depicted in Figure 15 for the three analysed tunnel depths. The results show a reasonable agreement for the shallower tunnels and particularly for the side towards the 1st Tunnel, although the proposal tends to underestimate the extent of the displacements for further distances. In contrast the prediction for the tunnel located at 28 m depth underestimate considerably the horizontal displacements in all profile, but mostly on the side towards the 1st Tunnel.

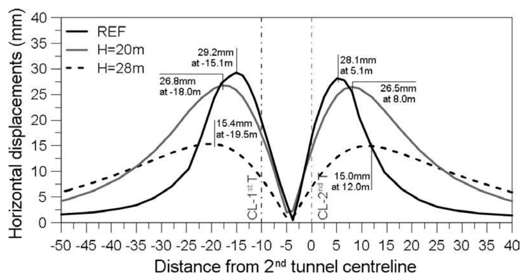

Figure 14. Influence of the depth of the tunnel on the horizontal displacements (absolute values).

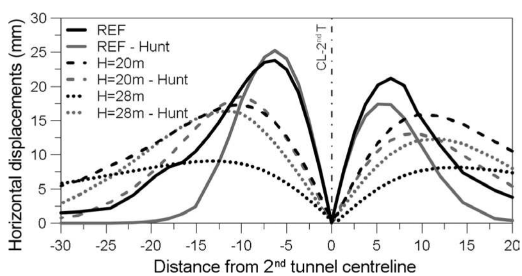

Figure 15. Influence of the depth of the tunnel on the 2nd Tunnel horizontal displacements (absolute values).

6 INFLUENCE OF THE PILLAR WIDTH

The influence of the pillar width between the two tunnels was analysed by performing five analyses were the spacing between tunnel was increased to 4, 8, 16, 24 and 36 m, corresponding to *L*/*D* ranges of 0.5 to 4.0. Apart from this change in the geometry all other parameters remained equal to those adopted in the reference analysis (REF).

Figure 16 presents the results of the final settlement troughs obtained for the different analyses. The results show that with the increase of the pillar width the settlements tend to decrease and the shape of the curve is modified. For *L*/*D* ratios smaller than 0.5 a generalised wide curve with a single peak, centred between the two centrelines of the tunnels, is observed. As the *L*/*D* ratio increases the curves became narrower and two peaks, approximately aligned with each tunnel, became distinct, meaning that the interaction effects tend to decrease for high *L*/*D* ratios. In fact, for values above 3 the curves of the two tunnels appear to be independent since there is an area of nearly zero vertical displacements between the two tunnels. Naturally these results are a consequence of the depth considered in the analysis and it is expected that the *L*/*D* ratio for which the transition of behaviour occurs might be different for other depth values. Similar conclusions can be drawn from the analysis of the horizontal displacements displayed in Figure 17. Also in this case the horizontal movements tend to diminish with the increase of the *L*/*D* ratio. For high values it is also possible to observe that two distinct curves are formed, each aligned with each tunnel centreline.

The influence of the pillar width in the displacements, both vertical and horizontal, is more perceptible in Figure 18. From the figure it is possible to verify that for *L*/*D* ratios above 2 there is almost no interaction effects between the tunnels.

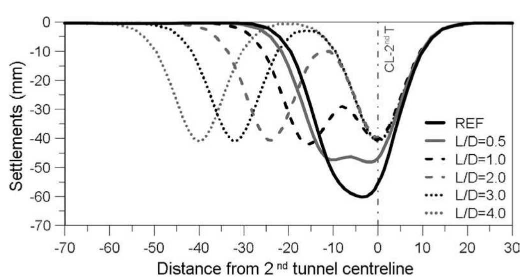

Figure 16. Influence of the pillar width on the settlement troughs.

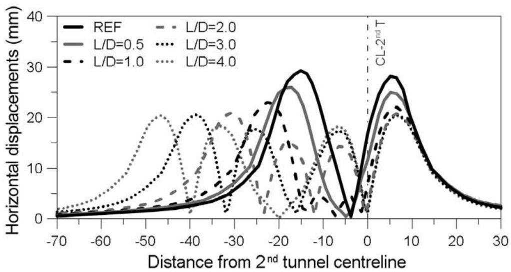

Figure 17. Influence of the pillar width on the horizontal displacements (absolute values).

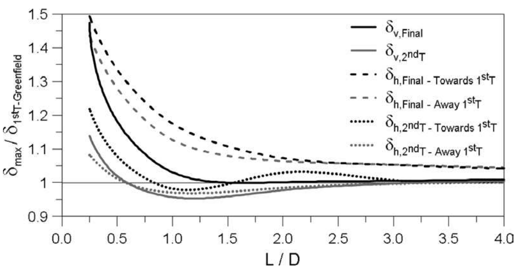

Figure 18. Influence of the pillar width on the maximum vertical and horizontal displacements.

For smaller ratios the interaction can lead to an increase of nearly 50% on the final vertical and horizontal displacements and up to 20% in the 2nd Tunnel. The decay of the influence is sharper on the final vertical settlements while it extends to further distances in the case of the final horizontal displacements. The modifications associated to the 2nd Tunnel show that there is a slight decrease of displacements in comparison with the greenfield scenario (less than 5%) for *L*/*D* ratios between 0.5 and 2. In the horizontal displacements a distinction was made between the two sides of the curve. Unsurprisingly the side towards the 1st Tunnel presents higher values when compared with the opposite direction (away 1st Tunnel). This behaviour was already observed in the other analyses performed and is due to the interaction effects that are more pronounced on the side where the 1st Tunnel is located.

A similar plot is presented in Figure 19 for the eccentricities observed in both vertical and horizontal maximum and minimum displacements, respectively. In this case it is possible to observe that for an *L*/*D* ratio higher than 1.5 there are no substantial differences, with the curves stabilizing at zero, i.e. no eccentricity of displacements. Maximum e_c/L of about 1.8 were found for an *L*/*D* ratio of 0.25. Also in this case it is possible to observe

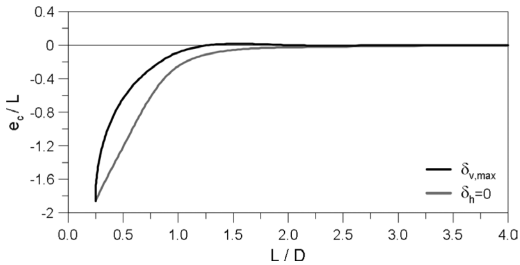

Figure 19. Influence of the pillar width on the eccentricity of the final displacements.

Table 7. Volume loss determined by the proposed methods for different pillar widths (%).

L/D	REF	Addenbrooke & Potts (2001)	Hunt (2005)	Divall 2013)	Ocak (2014)
0.5	2.42	2.67	2.50	3.00	3.10
1.0	2.41	2.61	2.40	2.89	2.91
2.0	2.40	2.55	2.33	2.48	2.71
3.0	2.40	2.49	2.33	2.44	2.62
4.0	2.40	2.49	2.33	2.30	2.56

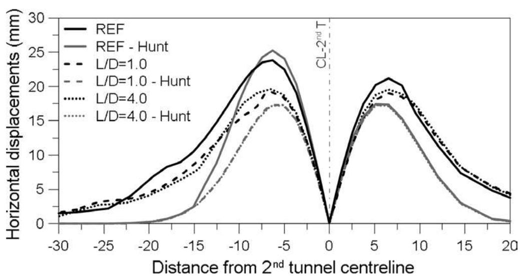

Figure 20. Influence of the pillar width on the 2nd Tunnel horizontal displacements (absolute values).

that the eccentricity associated to the maximum vertical settlement presents a sharp decay.

Table 7 displays the final volume loss obtained numerically (REF) and by the proposed empirical methods for the different analyses performed. The analysis of the results show an improvement of the adjustment with the increase of *L*/*D* in all methods. The differences observed for the analyses with high *L*/*D* are mainly related with the application of correction factors in some methods, despite the distance between tunnels. In terms of horizontal displacements it is possible to observe in Figure 20 that if the vectors of ground displacement are considered towards the crown of the tunnel the method proposed by Hunt (2005) provides a reasonable adjustment, regardless of the *L*/*D* ratio considered.

7 CONCLUSIONS

Based on the reference analysis performed it is possible to conclude that there are interaction effects when two side-by-side twin tunnels are sequentially excavated, with the 2nd Tunnel excavated presenting higher deformations and an eccentricity towards the 1st Tunnel which are not observed in a greenfield analysis, but typically found in real case studies. For the conditions and geometry simulated an increase of the volume loss of about 13% and an eccentricity of 0.37 times the spacing between tunnels towards the 1st Tunnel was obtained. The results also confirm that the interaction effects extend in depth with identical magnitude. The presence of the 1st Tunnel also affects the horizontal displacements induced by the excavation of the 2nd Tunnel. It was found that the side towards the 1st Tunnel is the most affected, with an increase of displacements of about 21% in comparison with the greenfield value. In the opposite side an interaction effect was also observed although smaller.

The comparison of the numerical results with the empirical methods proposed to predict the settlements revealed that all of them tend to overestimate the maximum settlement and the volume loss, although some can predict a similar eccentricity. From the methods proposed the best approximation was obtained employing Hunt (2005) expression. A better adjustment was achieved for the sub-surface displacements also using Hunt (2005) proposal. As for the horizontal displacements it was found that a better agreement was achieved if the vectors of ground movements were considered directed towards the tunnel crown and not to its axis as it is usually adopted.

The analyses performed considering deeper tunnels exhibit an identical behaviour, with the settlements induced by the 2nd Tunnel showing a similar increase of volume loss and a slightly higher eccentricity. The horizontal displacements confirm the asymmetrical behaviour, with higher values on the side towards the 1st tunnel regardless of the depth of the tunnels. The adjustment of the empirical expressions to the numerical results did not improve with the depth of the tunnels. One of the most important factors is the pillar width between tunnels. It was possible to conclude that for L/D ratios higher than 2 the interaction effects are negligible. For smaller ratios the influence grows exponentially and can reach an increase of nearly 50% of the final vertical and horizontal displacements. The results also show that with the increase of the pillar width the settlement trough changes its shape from being a generalised wide curve to become narrower and with two peaks aligned with the centrelines of the tunnels, showing a reduction of the interaction effects between tunnels. It was also found that the empirical methods tend to produce a better adjustment with the increase of L/D.

Naturally, the results presented in this paper were obtained for a particular set of conditions and parameters and further studies should be carried out in order to identify and evaluate the influence of other factors.

REFERENCES

Addenbrooke, T. I. & Potts, D. (2001) Twin Tunnel Interaction: Surface and Subsurface Effects. *International Journal of Geomechanics*, **1** (2), pp. 249–271.

Almeida e Sousa, J. (1998) *Tunnels in soils. Behaviour and numericalmodelling*. PhD thesis. University of Coimbra, Coimbra. (in Portuguese).

Bartlett, J. & Bubbers, B. (1970) Surface movements caused by bored tunnelling. In *Proceedings of the Conference on Subway Construction* sl]: Budapest-Balatonfured, Vol. 539.

Chapman, D. N., Ahn, S. K., Hunt, D. V. L. & Chan, A. H. C. (2006) The use of model tests to investigate the ground displacements associated with multiple tunnel construction in soil. *Tunnelling and Underground Space Technology*, **21** (3–4), pp. 413.

Cooper, M. & Chapman, D. (1998) Movement of the Piccadilly Line tunnels caused by the new Heathrow Express tunnels. *Proc. World Tun. Congr*, **98** pp. 249–254.

Cooper, M., Chapman, D., Rogers, C. & Hansmire, W. (2002) Prediction of settlement in existing tunnel caused by the second of twin tunnels. *Transportation Research Record: Journal of the Transportation Research Board*, (1814), pp. 103–111.

Cording, E. J. & Hansmire, W. (1975) Displacements around soft ground tunnels. In *Proceedings of the 5th Pan American Conference on Soli Mechanics and Foundation Engineering, Buenos Aires, Argentina.* Vol. 4, pp. 571–633.

Divall, S. (2013) *Ground movements associated with twin-tunnel construction in clay.* PhD thesis. City University London, London.

Hunt, D. V. L. (2005) *Predicting the ground movements above twin tunnels constructed in London Clay.* PhD thesis. University of Birmingham, Birmingham.

Janbu, N. (1967) *Settlement calculations based on the tangent modulus concept.* Trondheim, Technical University of Norway. pp. 57.

Mair, R., Taylor, R. & Bracegirdle, A. (1993) Subsurface settlement profiles above tunnels in clays. *Geotechnique*, **43** (2).

Mair, R. J. & Taylor, R. N. (1997) Bored tunnelling in the urban environment. In *Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering, State-of-the-art Report and Theme Lecture, Hamburg.* Balkema, Vol. 4, pp. 2353–2385.

New, B. M. & O'Reilly, M. P. (1991) Tunnelling induced ground movements: predicting their magnitude and effects. In *Proceedings of the 4th International Conference on Ground Movements and Structures, Cardiff.* Pentech Press, London, pp. 671–697.

Nyren, R. (1998) *Field measurements above twin tunnels in London Clay*. Imperial College London (University of London).

Ocak, I. (2014) A new approach for estimating of settlement curve for twin tunnels. In *Proceedings of the World Tunnel Congress'14, Istambul, Turquia*. pp. 1–6.

O'Reilly, M. P. & New, B. M. (1982) Settlements above tunnel in the United Kingdom—their magnitude and prediction. In *Proceedings of the Conference Tunnelling' 82, London*. Institution of Mining and Metallurgy, pp. 173–181.

Peck, R. B. (1969) Deep excavations and tunnelling in soft ground. In *Proceedings of the 7th International conference on soil mechanics and foundations engineering, Mexico City.* Vol. 3, pp. 225–290.

Potts, D. M. & Zdravković, L. (2001) *Finite element analysis in geotechnical engineering: application.* London.

Withers, A. D. (2001) *"Surface displacements at three surface reference sites above twin tunnels through the Lambeth Group" Building response to tunnelling,* pp. 735–754.