Proceedings 10th NUMGE 2023
10th European Conference on Numerical Methods in Geotechnical Engineering
Zdravkovic L, Kontoe S, Taborda DMG, Tsiampousi A (eds)

https://doi.org/10.53243/NUMGE2023-6

Influence of the pillar width on the construction sequence of twin tunnels

A. M. G. Pedro[1] , J. C. D. Grazina[2] , J. Almeida e Sousa[2]

[1]*ISISE, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal*
[2]*Department of Civil Engineering, University of Coimbra, Coimbra, Portugal*

ABSTRACT: Twin tunnelling has become frequent in large cities given the lack of space at ground surface and the need to have an adequate and efficient transportation network. In these systems the tunnels are usually built sequentially, i.e. with a considerable lagging distance between the tunnel excavation faces, though simultaneous excavation is also possible with the advantage of speeding up the construction and anticipate the operation stage. Regardless of the construction sequence adopted an important factor that affects the behaviour of both tunnels and the interaction effects between them is the pillar width. In order to assess its influence on the construction sequence of side-by-side twin tunnels a series of 2D finite element analyses were carried out. The numerical results show that the construction sequence has a residual impact for pillar widths higher than two times the diameter of the tunnels. However, for smaller distances a considerable interaction is observed, with the simultaneous excavation having a detrimental effect on the surface ground movements, while the sequential excavation induces considerably higher lining forces on both tunnels.

Keywords: Twin tunnels; pillar width; construction sequence; numerical modelling

1 INTRODUCTION

The construction of vast underground transportation networks has been the solution adopted by many cities all over the world to avoid congestion and pollution at ground surface (Broere, 2016; Cui & Nelson, 2019) with the advantage of being an asset that support, dynamize and leverage the economic development of the city (Admiraal & Cornaro, 2016). These networks often comprise the excavation of side-by-side twin tunnels, in which the traffic flows independently in opposite directions maximizing the speed while increasing efficiency and safety (Divall & Goodey, 2015). The tunnel excavation is usually performed sequentially, with a lagging distance between tunnel faces enough to ensure that a steady state condition due to the first excavation (1T) has been reached before the excavation of the second tunnel (2T), although simultaneous excavation, where the tunnel faces are approximately at the same position, can also occur near the end of the works with the approximation of the second excavation or to speed up the construction process and anticipate the operation stage.

The importance of the construction sequence and of the lagging distance between tunnel faces has been numerically investigated by Ng et al. (2004), Do et al. (2014b) and Do et al. (2016) using 3D analyses, with Ng et al. (2004) simulating the excavation of non-circular tunnels using the methodology proposed by the New Austrian Tunnelling Method (NATM) (Rabcewicz, 1964) and the latter studies simulating the excavation performed by a shield machine. Their results show that the lagging distance affects both the ground movements and the lining forces on both tunnels. For a lagged distance of zero (i.e. simultaneous excavation) a maximum settlement trough, centred at mid-distance between tunnels, was obtained, while minimum and symmetrical lining forces were determined in both tunnels. The results also showed that for a lagged distance of about 10 times the diameter (D) of the tunnel, steady state conditions due to the excavation of the 1T have been reached and, consequently, sequential excavation of the tunnels could be assumed. When compared with the simultaneous excavation a much smaller settlement trough but significantly higher lining forces on the 1T were observed in the sequential case, while the lining forces on the 2T remained approximately unchanged.

However, these studies were performed for a single pillar width (L) (L=1D in Ng et al. (2004) and L=0.25D in Do et al. (2014b) and Do et al. (2016)) and as demonstrated by small-scale, centrifuge and numerical models (e.g. Kim et al., 1998; Addenbrooke & Potts, 2001; Wu & Lee, 2003; Chapman et al., 2007; Do et al., 2014a; Divall & Goodey, 2015) this distance significantly influences the interaction between tunnels, particularly if L/D<2.00 in the case of sequential excavation. However, there are not published in the literature results that show the influence of the pillar width when the tunnels are driven simultaneously. In order to clarify this aspect and to evaluate the influence of the construction sequence on both surface ground movements and lining forces, a series of 2D numerical analyses of side-by-side twin tunnels were performed using PLAXIS v22.02 finite element program (Bentley Systems, 2022).

2 MODELLING PROCEDURES

Despite tunnelling being a 3D process, it has been shown that for steady state conditions, such as those obtained with simultaneous or sequential excavation, it can be modelled using 2D models as long as an appropriate approach is used to incorporate the 3D effects (Franzius et al., 2005; Karakus, 2007; Svoboda & Masin, 2011). In this work 2D plane strain analyses were carried out using the stress reduction method (Möller, 2006), which follows a two stages approach to simulate the 3D effects of the tunnel excavation. In the first stage the tunnel is excavated without the lining which is only applied in the second stage. However, only a percentage of the load due to the excavation is initially released (α=1-β) with the remainder (β) applied in the second stage. In this paper the stress reduction factor (α) was calibrated so that a volume loss (V_L) – ratio of the area of lost ground to the area of the excavated tunnel – of 0.50% was induced by the excavation of the 1T, i.e., in greenfield conditions. A α-value of 0.66 was determined for this particular case, which can be considered in line with the values obtained in previous studies (Möller & Vermeer, 2006). In order to cancel out any effect of the construction method the same α-value of 0.66 was adopted in the simulation of the 2T in all analyses. Consequently, modelling the sequential excavation required a total of four stages, first the left (1T) and then the right tunnel (2T), while the simulation of the simultaneous excavation only required two stages. Before the excavation of both tunnels the initial stresses were generated using a K_0 procedure.

As shown in Figure 1 the geometry adopted consisted of two 7 m diameter (D) tunnels with its axis located at a depth (H) of 17.5 m (ratio of cover (C) to diameter of 2.0). A total of six pillar widths (L) were considered, 1.5, 3, 6, 12, 18 and 24 m, corresponding to L/D ratios varying from 0.25 to 4.00. Naturally, the finite element meshes employed in the analyses were different according with the geometries adopted, with Figure 1 showing the case of the mesh employed in the L/D=1.00 model. In all analyses the tunnels were centred in the finite element meshes and to ensure the complete stabilisation of both stress and strain fields induced by the excavations a lateral distance of 72 m, measured from the centrelines of the nearest tunnel to the model external right/left border, was adopted, while the bottom boundary was placed at 21 m below the invert of the tunnels (Figure 1). In terms of boundary conditions, no horizontal displacements (d_h=0) were allowed along the lateral boundaries of the mesh, while at the bottom the displacements were constrained in both directions (d_v=0, d_h=0). No restriction of displacements was imposed at the top of the model, coincident with the ground surface. Drained conditions were assumed in all analyses and consequently no hydraulic boundaries were prescribed. The soil was discretized with 15-noded triangular elements, with cubic shape functions and 12 Gauss points for stress evaluation. For the lining of the tunnel, assumed to be composed of precast concrete segments with rigid connections, plate elements with appropriate axial and bending stiffness were employed. In order to improve the accuracy of the results a higher density of elements was considered around the tunnel and at ground surface (Figure 1).

The behaviour of the soil was simulated using the Hardening Soil model with small-strain stiffness - HSsmall (Schanz et al., 1999; Benz, 2006). To obtain a more realistic result the parameters derived for the silty-sand "Areolas da Estefânia" (AE) formation of the Miocene layer of the city of Lisbon were employed in this study and are presented in Table 1 (Pedro et al., 2017; Ferreira et al., 2018). The precast concrete segments were assumed to be linear elastic with a Young's modulus of 30 GPa, a Poisson's ratio of 0.2 and a thickness of 30cm.

Table 1. Soil parameters adopted for the AE formation

Parameter	Value
γ (kN/m^3)	20.0
c' (kPa)	4.0
φ'(°)	42.0
ψ (°)	11.6
E_{50}^{ref} (kPa)	38500
E_{oed}^{ref} (kPa)	18000
E_{ur}^{ref} (kPa)	100000
ν_{ur}	0.125
m	0.509
p^{ref} (kPa)	100.0
G_0^{ref} (kPa)	311500
$\gamma_{0.7}$ (%)	9.0E-4
K_0	0.7

3 SURFACE GROUND MOVEMENTS

The final settlements and absolute horizontal displacements obtained for the analyses with different pillar widths are plotted in Figures 2 and 3 against the distance to the pillar centreline normalised by the pillar width *Figure 2*for the sequential and simultaneous construction cases, respectively. In Table 2 the maximum settlements ($\delta_{v,max}$) and horizontal displacements ($\delta_{h,max}$), determined for the final stage are presented for ease of comparison. Regardless of the adopted construction sequence the settlement troughs present an identical behaviour with a single maximum peak observed for L/D<1.00, resembling a single larger excavation , while two peaks

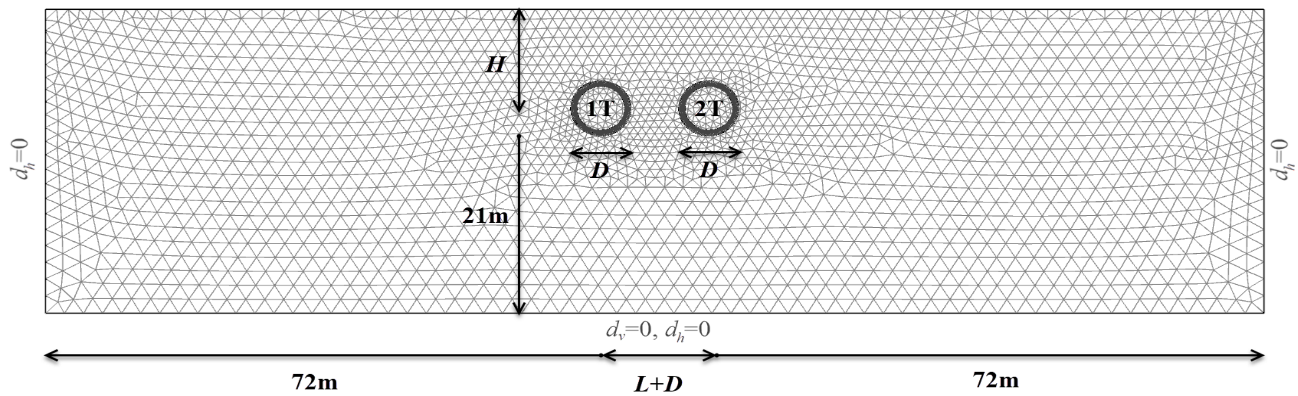

Figure 1. Layout of the geometry and finite element mesh for the model with L/D=1.00

became distinct with the increase of L/D, suggesting a decrease of the interaction effects. The horizontal displacements present an almost symmetrical distribution with a maximum value located on the external side of each tunnel. Again, for L/D<1.00 a single convergence point at approximately the pillar centreline is observed, while two convergence points (and one central divergence point) are visible for higher ratios.

However, in the simultaneous case the magnitude of the surface ground movements is much higher for L/D<2.00 (Table 2), reaching for the extreme case of L/D=0.25 maximums of 43.0 and 19.0 mm for the settlement and horizontal displacement, against 16.4 and 8.1 mm which are observed for the same L/D in the sequential case. The surface ground movements in both simultaneous and sequential cases tend to become similar with the increase of L/D ratio, with the exact same values (10.2 and 4.8 mm) being determined for the maximum L/D ratio (=4.00) in both cases (Table 2). These results confirm that for high L/D ratios (>2.00) the interaction between tunnels becomes negligible regardless of the construction sequence adopted.

The location of the maximum surface ground movements is marked in Figures 2 and 3 by the black open circles. In the sequential case the maximum settlement is almost located at the pillar centreline for L/D=0.25 and moves towards the 2T centreline for higher ratios, confirming that the 2T is more affected by the excavation. As expected, in the simultaneous case, for L/D<1.00 the maximum settlement is located at mid-distance between tunnels (pillar centreline) and for higher ratios two equal maximums are observed located symmetrically in relation to the pillar centreline and converging towards the centreline of each tunnel.

The position of the maximums horizontal displacements is identical and symmetrical in relation to the pillar centreline for both sequential and simultaneous cases. However, it is interesting to note that in the sequential case higher horizontal displacements are observed above the 1T, confirming the higher influence of the 2T excavation. Naturally, in the simultaneous case the maximum horizontal displacements present the exact same value above each tunnel.

Table 2. Maximum ground displacements

L/D		0.25	0.50	1.00	2.00	3.00	4.00
$\delta_{v,max}$ (mm)	Seq.	-16.4	-15.2	-13.1	-11.0	-10.7	-10.2
	Sim.	-43.0	-28.1	-17.1	-11.3	-10.4	-10.2
$\delta_{h,max}$ (mm)	Seq.	8.1	7.7	7.0	5.8	5.0	4.8
	Sim.	19.0	12.2	7.9	5.6	4.9	4.8

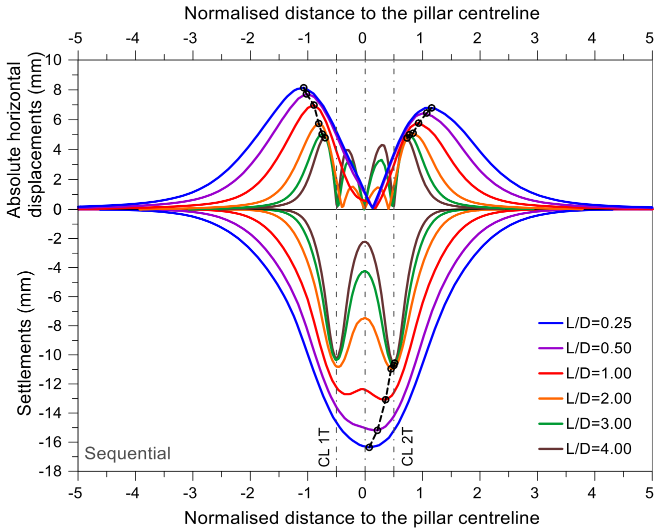

Figure 2. Surface ground movements obtained for the sequential construction case

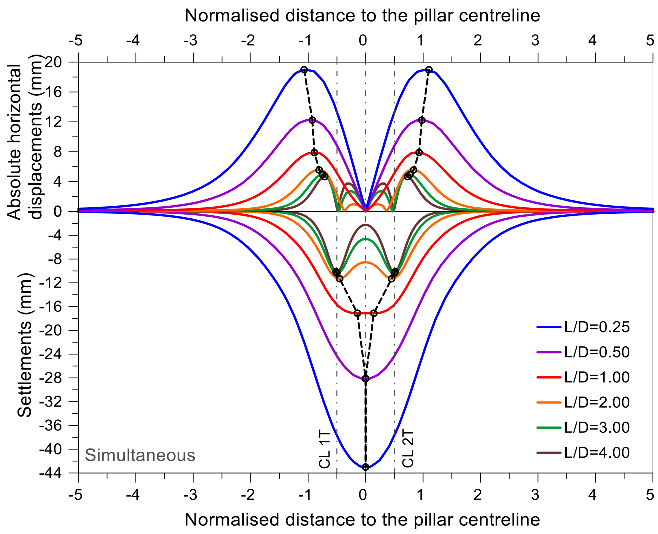

Figure 3. Surface ground movements obtained for the simultaneous construction case

4 LINING FORCES

The lining forces, hoop forces and bending moments, determined in both tunnels for the sequential and simultaneous cases are plotted in Figures 4 to 7. For ease of comparison the greenfield results, i.e. only due to the excavation of a single tunnel, are also depicted on the figures by a dashed black line. The results for L/D>2.00 were not represented in the figures as they were identical to those obtained in greenfield conditions confirming that no significant interaction effects occurred such L/D ratios. The maximum hoop forces and absolute bending moments mobilised in the lining of both tunnels are presented in Tables 3 and 4, respectively.

For the sequential case a considerable increase of the lining forces, particularly in the 1T, is observed with the decrease of the pillar width. In comparison with the greenfield results an increase of 168 and of 583% is obtained for the hoop forces and bending moments of the 1T, respectively, for the extreme case of L/D=0.25. For the 2T a more modest, but still relevant, increase of 16 and of 119% was determined. These differences are essentially located on the side of the pillar, with maximums at the tunnel springlines. However, it should be noted that the exponential increases observed in the bending moments are potentiated by the very small greenfield values (Table 4) and consequently should be considered carefully as they do not translate into a real significant increase of magnitude.

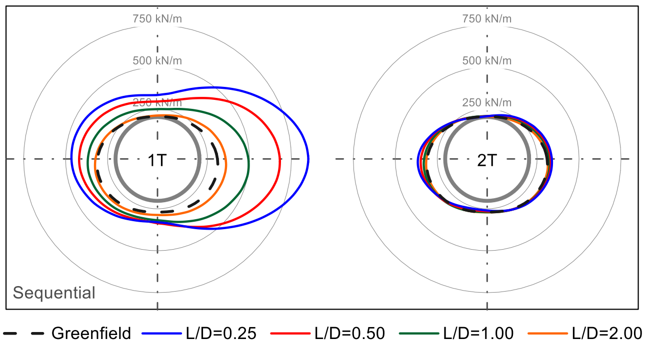

Figure 4. Final hoop forces acting on the lining of both tunnels for the sequential construction case

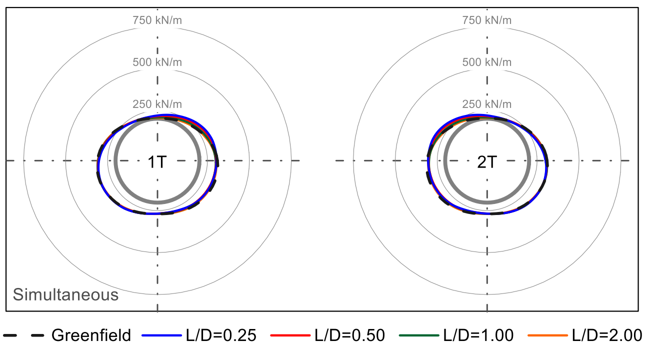

Figure 5. Final hoop forces acting on the lining of both tunnels for the simultaneous construction case

As expected, a completely different behaviour is observed in the simultaneous case, where the forces in both tunnels are equal and symmetrical in relation to the pillar centreline. As can be seen from the figures and tables the lining forces are in this case almost independent of the pillar width and present a similar magnitude to those determined in greenfield conditions, with the hoop forces being only slightly higher on the pillar side (Figure 5). This occurs since the released load on the final stage (34% of the total load due to the tunnels excavation) is equal on the contour of both tunnels and is almost entirely transferred to the linings due to its much higher stiffness.

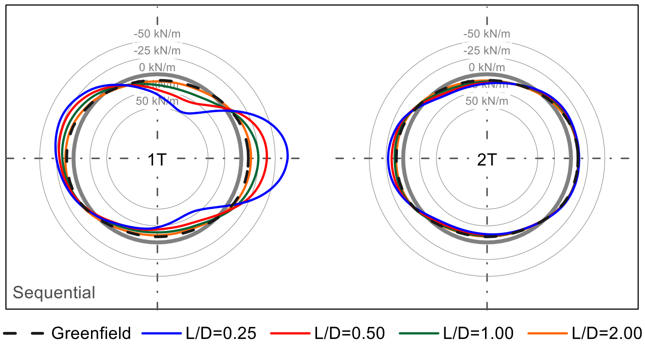

Figure 6. Final bending moments acting on the lining of both tunnels for the sequential construction case

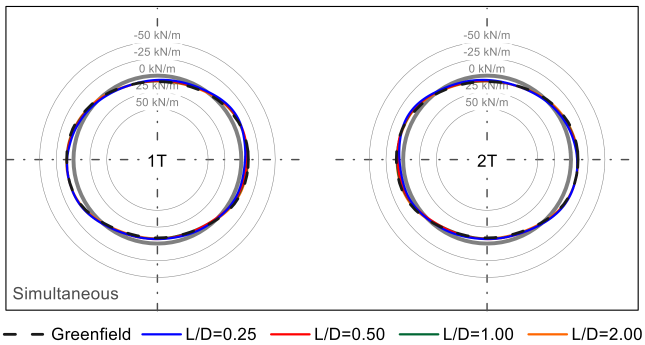

Figure 7. Final bending moments acting on the lining of both tunnels for the simultaneous construction case

Table 3. Maximum hoop forces (kN/m) mobilised in the lining

L/D		0.25	0.50	1.00	2.00	3.00	4.00
Greenfield		317.0					
1T	**Seq.**	851.4	681.4	498.0	364.1	320.3	317.0
	Sim.	313.7	314.2	316.0	314.4	315.6	315.7
2T	**Seq.**	366.7	349.5	333.3	320.6	316.0	315.5
	Sim.	313.7	314.1	315.9	314.3	315.5	315.8

Table 4. Maximum absolute bending moments (kNm/m) mobilised in the lining

L/D		0.25	0.50	1.00	2.00	3.00	4.00
Greenfield		9.9					
1T	**Seq.**	68.4	37.6	24.9	13.9	11.2	11.1
	Sim.	9.7	9.6	9.7	9.8	9.7	9.7
2T	**Seq.**	21.9	16.7	12.1	10.5	10.1	10.0
	Sim.	9.7	9.7	9.6	9.9	9.7	9.8

5 DISCUSSION OF THE RESULTS

To assess the influence of the construction sequence on both surface ground movements and lining forces the ratio between the maximum values observed in each case is plotted in Figure 8 against the pillar width. The results confirm that the simultaneous excavation has a detrimental effect on the surface ground movements for L/D≤2.00, with both settlements and horizontal displacements being significantly higher than 1 and increasing rapidly with the proximity of the tunnels. For higher ratios the surface ground movements are almost equal in the sequential and simultaneous case showing that there are no significant interaction effects between tunnels. The lining forces exhibit a contrasting behaviour, with the hoop forces and bending moments associated with the sequential excavation being higher than those determined in the simultaneous case. However, as observed in the surface ground movements, the difference between the lining forces determined for each case tends to decrease steadily with the increase of the pillar width and for a L/D=3.00 the impact of the construction sequence adopted becomes almost irrelevant. The figure also suggests that the lining forces are more sensible to the interaction between tunnels, although it should be referred that the bending moments are strongly influenced by the small amount of release load (34%) applied on the final stage of the excavation, as mentioned previously.

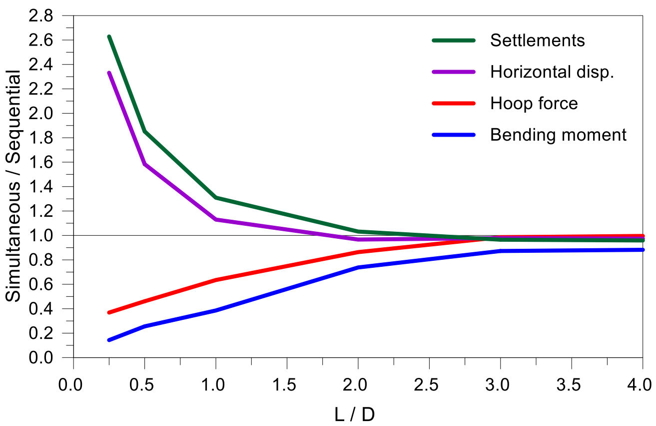

Figure 8. Influence of the construction sequence with the pillar width

6 CONCLUSIONS

Twin tunnelling has been adopted by many cities as a solution to improve the efficiency of the transportation networks. The construction sequence adopted in these systems is often sequential, with the tunnel excavation faces spaced apart, but in certain cases simultaneous excavation of both tunnels can occur. The numerical analyses performed confirmed that regardless of the construction sequence adopted the pillar width is a key factor that controls the behaviour and interaction between tunnels, with both surface ground movements and lining forces being significantly affected when the tunnels are closely spaced (L/D<2.00). Sequential excavation induces a considerable increase in the lining forces, particularly on the preceding tunnel (1T), while in simultaneous excavation the forces remain similar to those determined in greenfield conditions. In contrast, the surface ground movements associated with simultaneous excavation are significantly higher than those obtained with sequential excavation. These results show that both construction sequences have drawbacks, with sequential excavation having a detrimental effect on the lining forces and simultaneous excavation aggravating significantly the surface ground movements. However, the results show that for L/D≥2.00 the construction sequence adopted has a residual impact with both tunnels behaving almost independently.

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