Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0391

Numerical analysis of the lining forces induced by the excavation of twin tunnels in different soil conditions

Analyse numérique des forces de revêtement induites par l'excavation de tunnels jumeaux dans différentes conditions de sol

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ABSTRACT: In urban centres it has become frequent to excavate new tunnels in close proximity to existing ones. This scenario often leads to an interaction between tunnels, resulting in higher settlements at ground surface when compared with those obtained if the tunnels were excavated separately. This interaction has been analysed by several studies, but most of them are focused on the ground movements and disregard the effect of the second excavation on the lining forces of both tunnels. In this paper a numerical study of the sequential excavation of twin tunnels is carried out in order to further analyse this aspect. Finite element analyses are performed considering three different soil conditions, corresponding to soils with poor, fair and good mechanical properties. The influence of the pillar width between tunnels is also assessed by varying its value from 0.25 to 4 times the diameter of the tunnels. The results show that the excavation of the second tunnel can induce a significant increase in the lining forces of the existing tunnel for all soil conditions analysed. This increase is particularly relevant when the tunnels are closely spaced and when the soil is poor.

RÉSUMÉ: Dans les centres urbains, il est devenu fréquent de creuser de nouveaux tunnels à proximité des tunnels existants. Ce scénario conduit souvent à une interaction entre tunnels, qui peut entraîner une augmentation des tassements à la surface du sol par rapport à ceux obtenus si les tunnels étaient creusés séparément. Plusieurs études ont analysé cette interaction, mais la plupart d'entre elles se concentrent sur les mouvements du sol et ne tiennent pas compte de l'effet de la deuxième excavation sur les forces induites dans les revêtements des deux tunnels. Dans cet article, une étude numérique du creusement séquentiel de tunnels jumeaux est réalisée afin d'analyser en détail cet aspect. Des analyses par la méthode des éléments finis sont effectuées pour trois différentes conditions de sols, ayant de propriétés mécaniques faibles, moyennes et satisfaisantes. L'influence de la largeur des piliers entre les tunnels est également évaluée, en modifiant sa valeur de 0,25 à 4 fois le diamètre des tunnels. Les résultats montrent que le creusement du deuxième tunnel peut induire une augmentation significative des forces induites dans le revêtement du tunnel existant quelles que soient les conditions de sol analysées. Cette augmentation est particulièrement pertinente lorsque les tunnels sont étroitement espacés et lorsque le sol est faible.

Keywords: twin tunnels; lining forces; soil conditions; pillar width.

1 *INTRODUCTION*

With the growing development of urban areas, the transport networks at ground surface have been relocated to the subsoil making them more reliable and efficient. In this context, solutions such as side-by-side twin tunnels for metro, rail and even road traffic, have become increasingly common since they present several advantages in comparison with the more traditional approach of the excavation of a single tunnel with a larger diameter. One of the obvious is related with the safety and efficiency of the traffic flow, as in this solution there is a separation between the flow directions, which reduces significantly the number of collisions and enables the increase of speed. Other advantages are related with the excavation process itself, as the construction, for the same ground conditions, of a smaller tunnel is safer, requires less support and can be built at shallower depths reducing significantly the cost, without compromising the stability and safety. However, several case studies (e.g. Bartlett & Bubbers, 1970; Cording & Hansmire, 1975; Fargnoli et al., 2015) showed that when twin tunnels are constructed in close proximity interaction effects occur, leading to an increase of ground deformations and lining forces, which, ultimately, compromise their safety.

The behaviour of twin tunnels is also related with the sequence of the excavation. In the most common case the tunnels are considered to be driven sequentially, meaning that the excavation fronts are significantly spaced apart or that an old tunnel already exists in the vicinity of the new one. In these cases, the 2nd tunnel is excavated on a disturbed medium subjected to a modified stress field caused by the construction of the 1st tunnel. Furthermore, the excavation of the 2nd tunnel induces additional stress modifications and deformations on the ground, particularly on the pillar between tunnels, which directly affect the lining of the 1st tunnel. Therefore, the behaviour of the 1st and 2nd tunnel is expectedly different and influenced by the distance between tunnels, ground conditions and construction methods adopted in the excavation of both tunnels. The factors that affect the twin tunnels interaction have been investigated in the past using different approaches, which vary from small scale models (Kim et al., 1998; Chapman et al., 2007), centrifuge model testing (Wu & Lee, 2003; Divall & Goodey, 2015), analytical and empirical methods (Wang et al., 2018) and, more frequently, through numerical modelling (Ghaboussi & Ranken, 1977; Addenbrooke & Potts, 2001; Ng et al., 2004; Do et al., 2014; Do et al., 2015; Pedro et al., 2017). Despite the different approaches all studies concluded that the pillar width between tunnels plays an important role in the interaction. For values smaller than two times the diameter a generalised wide settlement trough with a single peak, centred between the two centrelines of the tunnels, is observed. As the pillar width increases two peaks, approximately aligned with each tunnel, became distinct, meaning that the interaction effects tend to decrease. As showed by Pedro et al. (2018) this distinct behaviour is justified by the stress redistribution that occurs in the central pillar, with the transfer of part of the load due to the 2nd tunnel excavation to the lining of the 1st tunnel. Despite this evidence there are not available in the literature many studies (Ghaboussi & Ranken, 1977; Do et al., 2014; Do et al., 2015) that analyse the interaction effects on the lining forces of both tunnels, with most being focused on the settlement troughs, stresses and deformations of the surrounding medium and on tunnels distortions.

In order to bring some insight to this subject a series of 2D finite element analysis of side-by-side twin tunnels excavated sequentially are performed and presented in this paper. The influence of the ground conditions was assessed by considering three distinctive idealised soil types with poor, fair and good mechanical properties. For each of those a series of analysis was carried out in order to evaluate the influence of the pillar width on the lining forces of both tunnels.

The numerical analyses were performed using the finite element code UCGeoCode, developed at the Department of Civil Engineering of the University of Coimbra (Almeida e Sousa, 1998).

2 *NUMERICAL MODEL*

2.1 *Model geometry and mesh*

The tunnels considered in the numerical analyses have a circular cross section with a diameter (*D*) of 6 m, lining thickness of 0.30 m and have their axis located at a depth (*H*) of 19 m (cover (*C*) of 16 m). The pillar width (*L*) varied from 1.5 to 24 m in order to assess the influence of this variable. A total of six distances between tunnels were considered with *L/D* ratios of 0.25, 0.50, 1.0, 2.0, 3.0 and 4.0. Consequently, six different finite element meshes were generated. In all of them a symmetrical vertical axis passing through the centreline of the pillar between the twin tunnels was considered. The lateral boundaries were located at a distance of 72 m measured from the axis of the nearest tunnel, leading to meshes with a total of 151.5 to 174 m wide. The bottom boundary was set at 24 m depth from the axis of the tunnels, resulting in a total height of 43 m for all meshes. The boundary conditions imposed restricted all movements perpendicular to the lateral boundaries, movements in all directions at the bottom and no restriction of movements at the top boundary. All materials in the model domain, soil and lining, were discretized with 8-noded isoparametric elements. Figure 1 presents the finite element mesh employed for the particular case of the *L/D*=1.0, where is possible to observe the refinement of the mesh on the areas around the tunnels.

2.2 *Parameters of the materials*

Three idealised types of soil with different mechanical properties, which represent poor, fair and good ground conditions, were considered. In all the cases an elastic-perfectly-plastic soil model with a Mohr-Coulomb failure criterion was adopted with parameters defined according with the quality of the ground (Table 1). The deformability modulus, *E*, was evaluated by Equation 1 (Janbu, 1967) at each Gauss point of the model.

Table 1. Mechanical parameters of the soils

Soil	**φ'**	**c'** (kPa)	**ψ**	**A**	**ν**
Poor	25º	5	0º	200	0.3
Fair	35º	5	5º	400	0.3
Good	45º	5	8º	800	0.3

$$E = E_0 + A \cdot p_a \left(\frac{\sigma_3}{p_a}\right)^n \qquad (1)$$

In the equation E_0 corresponds to the deformability modulus at ground surface (defined as 5000 kPa), p_a is the atmospheric pressure (100 kPa), σ_3 is the confining stress and the values of *n* and *A* are constants of the model. A value of *n*=0.5 was adopted for all the analyses, while the parameter *A* was adjusted depending on the soil type. The value of *E* was updated throughout the analysis at the end of each stage depending on the value of the confining stress.

The same initial geostatic stress state was considered for all types of soil, with a unit weight (γ) of 20 kN/m^3 and an earth pressure coefficient (K_0) of 0.6. Dry conditions were also assumed in all analyses.

For the lining of the tunnels a linear elastic behaviour, with a Young's modulus of 20 GPa and a Poisson's coefficient of 0.2, and a unit weight of 25 kN/m^3 was assumed.

2.3 *Construction sequence*

A sequential construction in full section of the tunnels was considered in all analysis, with the left tunnel being excavated first (1st Tunnel). The 3D effects related to the construction process were introduced in the 2D analyses following the principles of the convergence-confinement method (Potts & Zdravković, 2001). In the first step the elements inside the tunnel were removed but only part of the released forces, corresponding to a stress release factor of α=0.4, were applied in the excavation contour. In the second step the lining was installed and the remainder unbalanced forces (1-α) applied, so that a final state of equilibrium was reached. This process was repeated for both tunnels given a total of 4 stages.

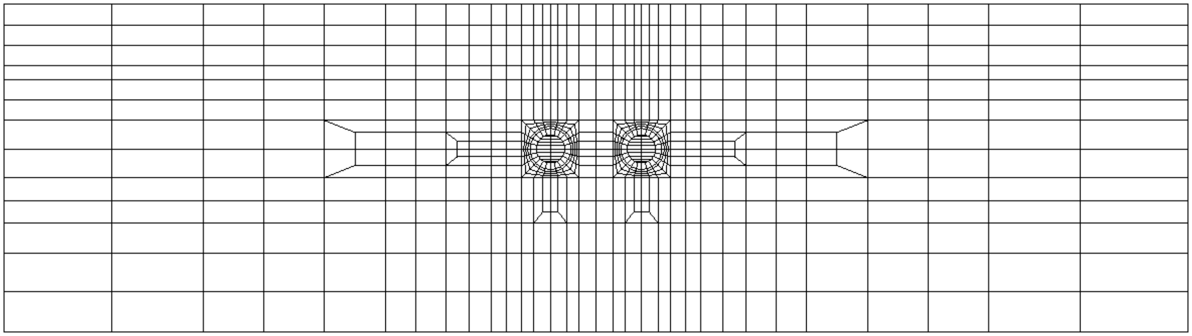

Figure 1. Finite element mesh (model with L/D=1.0)

3 *EXCAVATION OF THE 1ST TUNNEL*

The results of the hoop forces and bending moments acting on the lining of the 1st Tunnel at the end of its construction (2nd stage) for the three types of soil are depicted in Figure 2. Since this tunnel is excavated in greenfield conditions the forces have symetric distributions relative to the vertical axis of the tunnel, with only a very small difference observed in the values determined at the crown and invert due to the increase in depth of the initial geostastic forces. Since the K_0 value is smaller than 1 higher hoop forces are observed on the springline of the tunnel, reaching about 440 kN/m. It is also interesting to observe that the soil type has a minimal influence on the hoop force, being almost equal in all cases. These results suggest that, although the stress release is equal in all analyses, the lining response appears not to be significantly influenced by the different soil properties.

However, a distinct behaviour is noticeable on the bending moments (Figure 2b)) with an increase of positive and negatives values, at the springline and crown/invert, respectively, for poorer ground conditions. These results are in agreement with the flexibility concept (deformability ratio between the surrounding medium and lining) proposed by Peck et al. (1972) where flexible tunnels (good ground conditions) induce smaller bending moments and rigid tunnels (poor ground conditions) the opposite, i.e., higher bending moments.

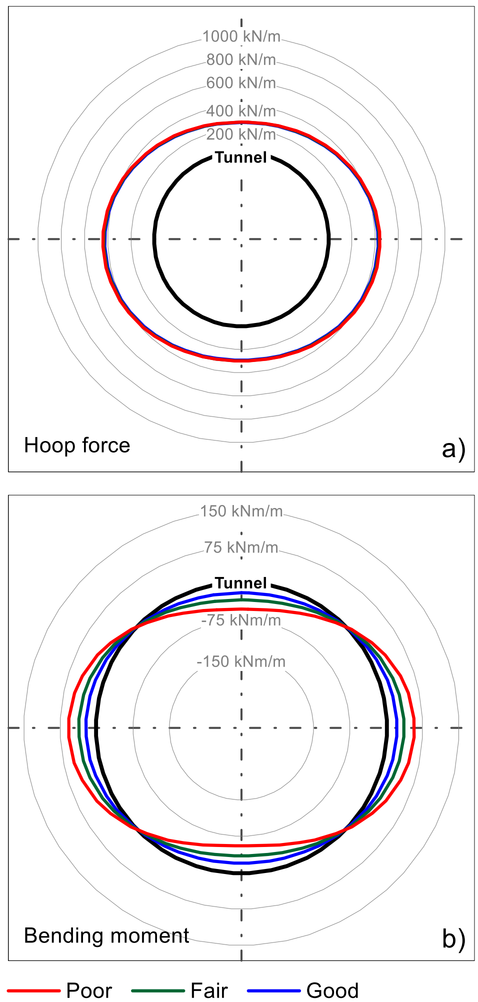

Figure 2. Diagrams of the forces acting on the lining of the 1st Tunnel for the 2nd stage of the analysis: a) hoop force; b) bending moment

4 *EXCAVATION OF THE 2ND TUNNEL*

The results of the final lining forces acting on the 1st and 2nd Tunnel are depicted in Figure 3 and Figure 4, respectively. With the purpose of ilustrate the influence of the pillar width on the lining forces results for three different ratios of *L/D* are presented in the figures. The ratios of *L/D*=0.25 and of 4.00, represent the extreme cases when the tunnels are closely spaced and far apart, and the *L/D*=1.00 corresponds to a more common scenario.

The analysis of Figure 3 shows that there is a substantial interaction between tunnels for the smaller *L/D* ratio. Both hoop forces and bending moments are no longer symetrical with higher values observed on the side of the 2nd Tunnel, although increases are also observed on the other side. The magnitude of the forces is directly related with the ground conditions, with higher values corresponding to the poorest conditions. For that case the hoop forces reach a maximum of 1060 kN/m, while the maximum and minimum bending moments, located at the right springline and crown have absolute values of about 160 kNm/m and 120 kNm/m, respetively.

In contrast, for the largest pillar width (*L/D*=4.00) the lining forces (hoop and bending moments) remain similar to those determined after the construction of the 1st Tunnel (Figure 2), suggesting that for this distance between tunnels there are no interaction effects caused by the construction of the 2nd Tunnel.

For the intermediate pillar width (*L/D*=1.00) an increase on the lining forces of the 1st Tunnel is also observed, although with a much smaller magnitude than that verified for an *L/D*=0.25. Also on this case an assymetric distribution of the lining forces is determined, with higher values on the side of the 2nd Tunnel. The increase of forces due to the soil conditions is mainly visible on the

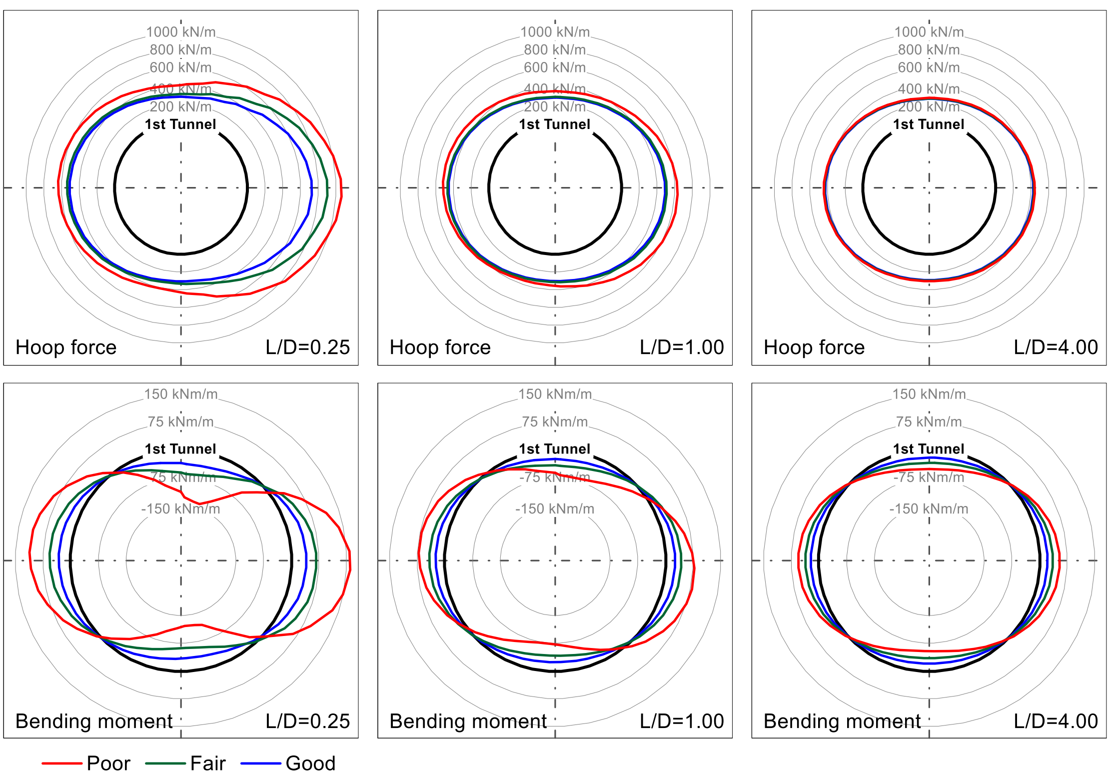

Figure 3. Diagrams for different normalised pillar widths (L/D) of the hoop force and bending moment acting on the lining of the 1st Tunnel for the final stage of the analyses

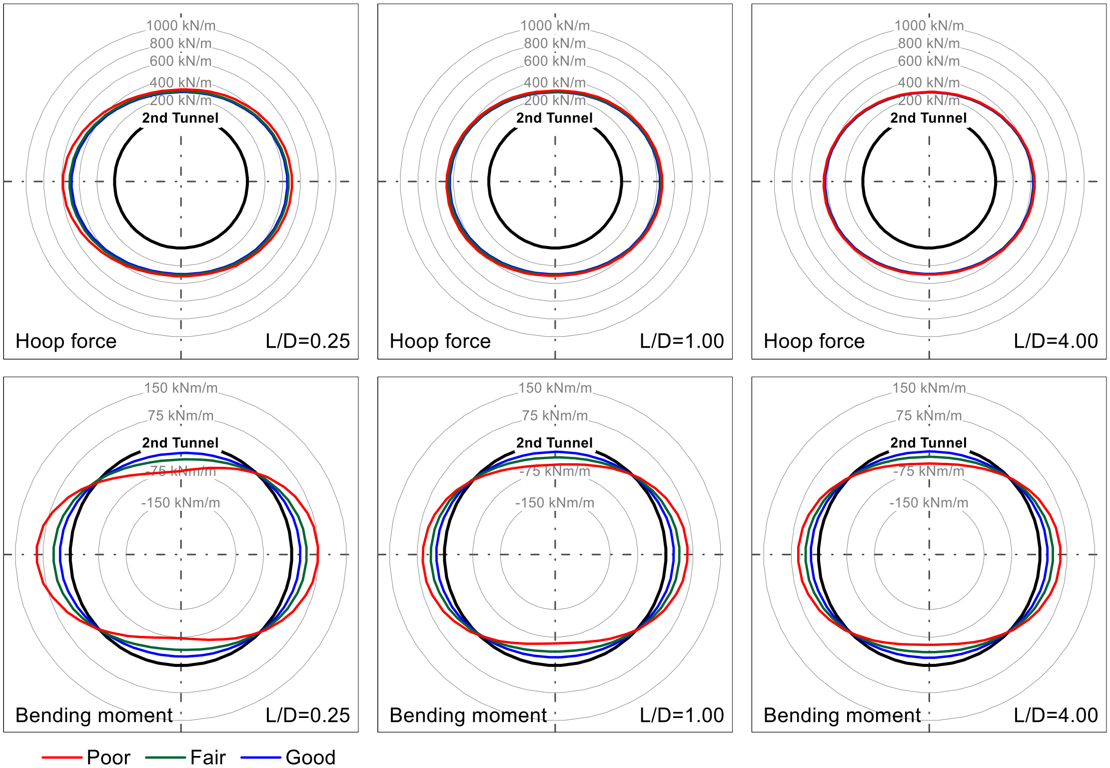

Figure 4. Diagrams for different normalised pillar widths (L/D) of the hoop force and bending moment acting on the lining of the 2nd Tunnel for the final stage of the analyses

bending moments since on the hoop forces the fair and good soil types provide similar values.

The forces acting on the 2nd Tunnel after its completion (Figure 4) appear to be similar to those observed after the construction of the 1st Tunnel (Figure 2) for the cases where L/D≥1, suggestion that the presence of the 1st Tunnel had a minor influence over the 2nd Tunnel. These results appear to be independent of the ground conditions with the differences being almost imperceptible in all cases. For the extreme case of *L/D*=0.25 it is possible to observe that some interaction occurs, particularly when poor ground conditions are considered. In this case an asymmetric increase of forces, hoop and bending moment, is visible on the side of the 1st Tunnel at the springline level, although its magnitude is reduced when compared to that observed on the 1st Tunnel. The obtained results show that the 1st Tunnel is more affected by the 2nd excavation, particularly for smaller *L/D* ratios, while a minimal interaction is visible on the 2nd Tunnel, despite being excavated on disturbed ground and stress conditions.

5 *INFLUENCE OF THE PILLAR WIDTH*

The interaction effect can be expressed by the ratio between the maximum value of the final forces acting on the lining of both tunnels and the forces determined after the construction of the 1st Tunnel (greenfield scenario). The obtained ratios for both the hoop forces and bending moments of both tunnels are presented in Figure 5 for the six *L/D* ratios considered (varying from 0.25 to 4.0) and for all ground conditions analysed. In the figure the solid lines represent the interaction effect observed on the 1st Tunnel while the dashed lines correspond to the 2nd Tunnel. The results show that regardless of the type of soil the final hoop forces and bending moments are higher than those measured in the greenfield scenario, with the ratio increasing considerably with the proximity of the tunnels (smaller *L/D*). For the hoop forces an interaction effect is still visible to about an *L/D*=3.0 in both tunnels, although for values higher than 2.0 in the 1st Tunnel and 1.0 in the 2nd Tunnel, respectively, the interaction is minimal. In terms of the bending moment the extent of the interaction is smaller and for L/D higher than 2.0 for the 1st Tunnel and 1.0 for the 2nd Tunnel can be neglected. It is also possible to confirm that the interaction affects mainly the 1st Tunnel where much higher ratios are observed regardless of the type of force and of the ground conditions. As expected, for poorer ground conditions the ratios tend to increase, with a visible difference being observed for the poorest conditions analysed, where a much higher ratio is estimated. For fair and good ground conditions there are only noticeable differences for *L/D* smaller than 0.5, with the ratios being similar for higher *L/D* values. The ratios obtained for the bending moment are higher than those observed for the hoop forces, suggesting that this type of force is more affected by the interaction. It is interesting to note that even for fair ground conditions and for the smallest *L/D* (=0.25) analysed the excavation of the 2nd Tunnel will induce an increase on the forces of the 1st Tunnel that can double its initial value, meaning that the tunnel should be designed for such overload. In the 2nd Tunnel itself an increase of around 25 % should be accounted for.

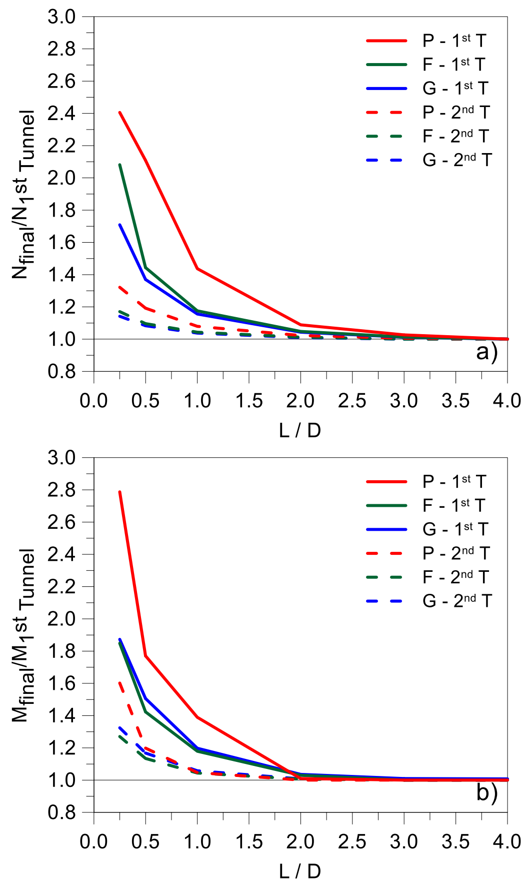

Figure 5. Influence of the pillar width on the lining forces: a) hoop force; b) bending moment

6 *CONCLUSIONS*

Based on the results of the analyses performed the following conclusions can be drawn:

i) The interaction effects increase significantly with the proximity of the tunnels and for poorer ground conditions; and are particularly relevant for the lining forces (for both hoop forces and bending moments) of the 1st Tunnel, being also noticeable on the lining forces of the 2nd Tunnel;

ii) For *L/D* ratios higher than 2 the interaction effect on the lining forces of the 1st Tunnel can be neglected; while for the 2nd Tunnel the interaction is mainly relevant for ratios smaller than 1.0;

iii) With the excavation of the 2nd Tunnel an asymmetric behaviour is observed on the lining of both tunnels with a higher increase of the forces on the central pillar side; these can reach twice the greenfield value on the 1st Tunnel and about an increase of 25% on the 2nd Tunnel, even for fair ground conditions, reaching higher values for poorer conditions;

iv) The increase of the lining forces is linked to the quality of the ground conditions, although soils with fair and good properties present a similar behaviour; for soils with poor conditions a significant increase of the interaction effects are observed.

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