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2D numerical investigation of twin tunnels-Influence of excavation phase shift

Chafia Djelloul*[1,2], Toufik Karech[2], Rafik Demagh[2], Oualid Limam[3] and Juan Martinez[4]

[1]Department of Civil Engineering, Faculty of Technology, Batna 2 University, 53 Street of Constantine, Fésdis, CP 05078 Batna, Algeria
[2]Department of Civil Engineering, Mohamed El Bachir El Ibrahimi University, 34030 Bordj Bou Arreridj El-Anasser, Algeria
[3]Laboratory of Civil Engineering, University of Tunis El Manar, National Engineers School of Tunis, BP 37, 1002 Tunis Le Belvédère, Tunisia
[4]Laboratoire GCGM, National Institute of Applied Sciences, 20 avenue Buttes de Coësmes CS 70839 - 35 708 RENNES Cedex 7, France

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Abstract. The excavation of twin tunnels is a process that destabilizes the ground. The stability of the tunnel lining, the control of ground displacements around the tunnel resulting from each excavation and the interaction between them must be controlled. This paper provides a new approach for replacing the costly 3D analyses with the equivalent 2D analyses that closely reflects the in-situ measurements when excavating twin tunnels. The modeling was performed in two dimensions using the FLAC2D finite difference code. The three-dimensional effect of excavation is taken into account through the deconfinement rate λ of the soil surrounding the excavation by applying the convergence-confinement method. A comparison between settlements derived by the proposed 2D analysis and the settlements measured in a real project in Algeria shows an acceptable agreement. Also, this paper reports the investigation into the changes in deformations on tunnel linings and surface settlements which may be expected if the twin tunnels of T4 El-Harouche Skikda were constructed with a tunneling machine. Special attention was paid to the influence of the excavation phase shift distance between the two mechanized tunnel faces. It is revealed that the ground movements and the lining deformations during tunnel excavation depend on the distance between the tunnels' axis and the excavation phase shift.

Keywords: tunnel; interaction; numerical-simulation; convergence-confinement; excavation phase shift

1. Introduction

The construction of a shallow tunnel inevitably requires modifications in the distribution of stresses around the underground structure and therefore causes deformations in the ground. In congested cities, the excavation of twin tunnels in close proximity has recently increased. A great amount of research has been conducted on tunnel interaction between two parallel tunnels. A review of the laboratory model tests of tunnels in soft soils has been presented to better understand soil movements induced by tunneling (Hajihassani *et al.* 2014). Field and model tests have been carried out by He *et al.* (2012) based on Chengdu Metro Line1 in China and found that when the distance between the tunnels axes reaches twice the tunnel diameter two independent collapsed arch was formed on top of each tunnel and the interaction between two tunnels can be neglected. A finite element model (FEM) *proposition has been made* by Mazek (2011) to predict the performance of tunnel system based on the twin tunnel construction of El-Azhar road tunnels. The interaction between a newly built tunnel and its adjacent existing tunnel in the special ground condition in Beijing were studied by Chengping *et al.* (2014), they carried out several numerical simulations on parallel twin tunnels with different angles and different spacing. Chehade and Shahrour (2008) used three configurations of twin-tunnels aligned horizontally, vertically and inclined in order to compare the shape of settlement trough on the ground surface. They found that the construction procedure affects the soil settlement and internal forces in linings. An investigation of the factors affecting the stress distribution around two circular tunnels and the internal forces in linings were performed by Elsamny *et al*. (2016), they found that modulus of elasticity, Poisson's ratio for the soft clay soil, vertical distances between the two tunnels and horizontal distances between the center-line of two tunnels are some of the factors that affect the stress distribution and the surface settlement. A two-dimensional numerical model was used (Hansmire *et al*. 2004), in order to examine the interaction between multiple tunnels in soil with shotcrete linings on TrenUrbano, San Juan, Puerto Rico, they carried out numerical analyses to correctly determine the loading conditions to structurally design the primary linings. They found that linings installed first in the sequence assumed more load and required more structural capacity with greater thickness, while linings installed later could be thinner with less reinforcing, they reveal that the excavation sequence is very important as significant loads can be transferred to existing tunnels when an adjacent excavation takes place.

The influence of the construction process between the twin-shield tunnels using full 3D finite element method was investigated by Do *et al.* (2014a). They pointed out that the simultaneous excavation of twin tunnels could result in a higher settlement above two tunnels. An analytical solution to study the interaction between twin parallel tunnels was

*Corresponding author, Ph.D. Student
E-mail: chafia.djelloul@yahoo.com

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presented by (Fu *et al.* 2015), the comparisons of the surface displacements from proposed analytical solution and the principle of superposition reveal that the interaction between twin tunnels affects the surface displacement which diminishes with the increase of tunnel depth and the increase of spacing between two tunnel axes. A 2D numerical investigation to predict the impact between two tunnels was performed by Do *et al.* (2014b). The effects of distance between tunnels on the structural forces induced in both tunnels were examined. Among their conclusions, the existing tunnel is affected to a greater extent by the construction of the second tunnel, however, the existing tunnel only causes a slight impact on the new tunnel, the behaviour of the new tunnel is similar to that of a single tunnel. Chapman *et al*. (2006), used a model test to investigate the ground displacements associated twin tunnels construction, results obtained followed similar trends as those obtained from field data. Divall *et al*. (2014), focused on the influence of time delay between the construction of each tunnel, compared with tunnels constructed simultaneously on the surface settlement. A 3D numerical investigation was carried out (Do *et al*. 2016), in order to study the interaction between mechanized tunnels excavated in horizontally parallel section, they paid special attention to the influence of the lagging distance between the two mechanized tunnel faces. Other works focus on the effects of the following tunnel on the preceding one Addenbrooke and Potts (2001), Shahin *et al*. (2016). In their researches, it was found that surface settlement profiles depend on the location of the following tunnel. Some other researchers such as Mirhabibi and Soroush (2012), Hasanpour *et al*. (2012), carried out numerical analyses to examine the interaction between two adjacent tunnels as well. Most of the previous research focused on the interaction between tunnels based on the influence of the spatial localization of the two tunnels in terms of ground deformation, but not the structural forces induced in tunnel linings. The literature works on the 3D numerical simulations which considers the influence of the lagged distance between the two tunnels' faces on the ground displacement and lining deformation is rather limited (Ng *et al*. 2004, Do *et al*. 2016). A literature review also reveals that a 2D numerical simulation for twin circular tunnels that allows both ground displacement and structural lining forces to be taken into consideration with the advancement of tunnels is not available. In this study, the ability of a 2D numerical approach to reproduce the real behavior of the twin tunnels measured in-situ by introducing the excavation phase shift factor, which is a truly 3D problem, was tested using FLAC2D (finite difference program), this issue is of major interest for twin tunneling operation. We suppose that a tunneling machine was used in construction. Due to its flexibility, this method is applied to modeling the twin excavation in geological and geometrical conditions corresponding to the T4 tunnel from El-Harouche Skikda adopted in this study as a real reference case. We paid special attention to the influence of excavation phase shift of the two tunnels on the stability of ground surface and internals forces in linings. The *aim of this study* is to provide a new simplistic approach for replacing the costly 3D analyses with an equivalent 2D approach that closely reflects the in-situ measurements when excavating twin tunnels.

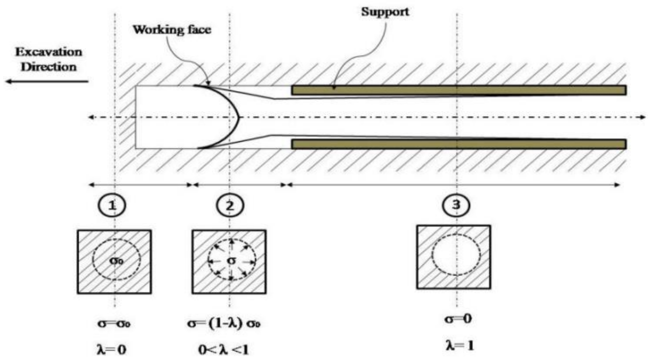


Fig.1 Stress reduction method (Panet and Guenot1982)

2. Convergence-confinement method (CCM)

The convergence-confinement method (CCM; (Panet and Guenot 1982), (Hejazi *et al*. 2008)) is a simplified theory that allows 3D tunneling effect to be taken into consideration when modeling this process by a 2D plane-strain analysis. This theory allows the pre-displacement of the ground surrounding the tunnel, before the lining installation, to be taken into account, by applying a stress release ratio (λ) (Do *et al.* 2014c, Wang *et al*. 2017) (Fig. 1). The numerical modeling is performed in 2D. The three-dimensional effect of excavation as aresult of the advancement of tunnel face is taken into consideration by applying the CCM through the stress release ratio λ which consists in applying a stress to the excavation circumference given by $\sigma = (1-\lambda)\sigma_0$, where σ_0 is the initial stress of the ground and λ is the stress release ratio varying from 0 to 1 to simulate the impact produced by advancing excavation (Fig.1). Equivalence between 3D and a 2D plane strain problem is widely used in tunneling and other engineering applications. In this paper it is applied to the case of twin tunneling offset. According to the research performed by Karakus (2007), Do *et al.* (2014c), Do *et al*. (2013), Wang *et al*. (2017), Oreste (2003, 2009), Janin (2012), Mousivand *et al*. (2017), the convergence-confinement method (CCM) can be applied efficiently for our purpose. The CCM will be applied in this study to quantify the impact of a change in the excavation phase shift distance on the behaviour of soil above two circular tunnels through varying the stress release ratio of the right tunnel. We put λ_L as the stress release ratio related to the release of radial stress around the left tunnel opening, λ_R as the stress release ratio related to release of radial stress around the right tunnel opening. As the excavation phase shift of tunnel depends on the deconfinement process and lining installation (Fig. 1), it is implicitly assumed that the phases of setting up the linings of the two tunnels are similar, so the excavation phase shift (P_s) of the two tunnels only depends on the deconfinement process around each tunnel. It is pointed out that as λ increases the ground loses its confinement and a higher radial displacement towards the tunnel medium will be allowed so we can admit that when λ increases the excavation phases shift increases. Empirical Eq. (2) indicates that the stress released ratio tends to one when the tunnel is finished, which is reasonably far from the tunnel boundaries. Based on this purpose a comparison with in-situ measurements obtained from the excavations of the T4 tunnel of El-Harouche Skikda was made in order to validate the numerical simulation and to prove the efficiency of the new 2D approach equivalent to a 3D analyses.

3. Location and site geology

The T4 tunnel is part of Section 4 of the East-West Highway in Algeria passing through Djebel El-Kantour in the northeast of the city of Constantine with a total length of 2500 m. The on-site geotechnical investigation indicates that the area in question is mainly composed of marl and altered argillites overlain by conglomerate and clay. The maximum tunnel overburden thickness is approximately 235 m. The most critical section, which corresponds to the lowest overburden thickness, was 17 m below the ground surface. This motorway tunnel comprises two tubes with a space distance of 37 m between the two tunnel centers.

The modeled section selected in this study (Fig. 2), which has been adopted as a reference case, is completely located in clays and compact marl and coincides with the area of smaller overburden thickness on the site. For the purpose of introducing the excavation phase shift factor, a typical cross-section is chosen (affected area) as illustrated in Fig. 2. The section is located at the mileage K=229+251.5, this section is considered stable and doesn't require reinforcement. The twin tunnels are supposed to be circular with a diameter *D*=15m excavated at a depth of 17.9m below the ground surface. Five cases of horizontal tunnel distance d_x that is 1.5*D*, 1.75*D*, 2*D*, 2.25*D*, and 2.5*D* were simulated, d_x=2.5*D* corresponds approximately to the same location of the twin tunnels at T4 tunnel of El-Harouche in the section selected (Figs.2 and 3). The settlement measurements taken during its construction were employed to validate the results of the analyses undertaken. Table1 summarizes the properties of the soil and the lining used in this study.

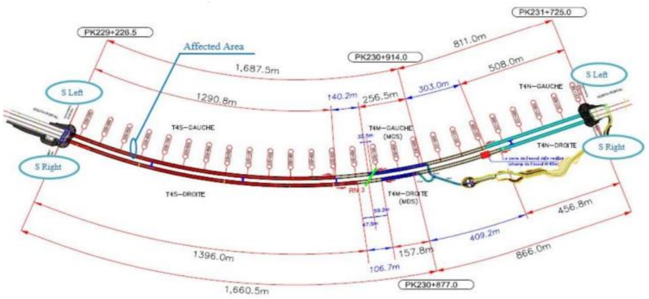


Fig. 2 Plan view and longitudinal section of tunnel T4

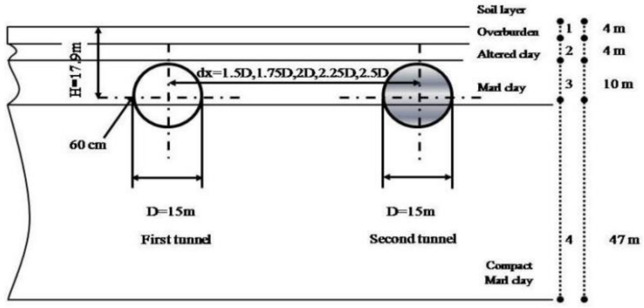


Fig. 3 Geological conditions and typical cross-section of the two tunnels view

Table 1 Physico-mechanical parameters of surrounding soil and lining (Dar al-handasah-shair 2008)

Depth (m)	Elastic modulus	Poisson's ratio	Unit weight γ (kN/m^3)	Cohesion c(kPa)	Friction angle, ϕ(°)	Thickness (m)
0-4	5	0.3	16.5	5	27	4
4-8	25	0.3	17.5	5	27	4
8-18	140	0.3	20	10	20	10
18-65	240	0.3	22	25	22	38
Lining	12.639e3	0.3	25			0.6
0-4	5	0.3	16.5			4

4. Numerical modelling

4.1 Boundary conditions

The soil is modeled as an elastoplastic medium with a Mohr-Coulomb failure criterion. In this study, only primary linings were considered and they were modeled by continuous beam elements with linear elastic behavior and a perfect bonding with soil. This remains a plane stress simplified model of the lining, which is concreted piece by piece with joints and which can be justified by the fact that internal forces (normal force and bending moment) induced in these circular beams leads generally to compression at the surface contact between joints with continuous normal stresses and totally compressed beam sections. The model dimensions were 180m (width) x 65m (depth); the lateral extension of the soil mass is equal to 12*D* which ensures the absence of lateral boundary effect on the numerical modeling of the tunnel construction. Concerning the boundary conditions, the displacements are constrained in both directions at the bottom, while zero horizontal displacements are imposed at the two laterals boundaries. The FLAC2D grid contains two layers of zones in the vertical direction and three layers of zones in the horizontal direction. The dimension of the elements increases as one moves away from the twin tunnels' axes. To obtain more accurate results, a non-uniform finite difference mesh was used with smaller elements around the twin excavations. The water table was considered, located at a great distance below the level of twin tunnels invert. Thus, all calculations performed in this study did not consider the presence of a a water table. Because of the particular characteristics of the problem in tunnelling engineering, numerical investigation performed in this study examine the application of 2D numerical analysis of mechanized tunneling by using a double shield TBM, considering many factors that take place during tunnel excavation such as the generation of initial stress fields, the excavation of ground medium, the installation of the lining segments and the machine advance. The twin tunnel excavation sequence using the CCM was modeled as described in section (4.2 simulation phases).

The ground in which the twin tunnels emplaced is considered undisturbed.

4.1 Simulation phases

The twin tunnels excavation phases were simulated using the convergence-confinement process with the following steps:

-Across-section model is generated for the two tunnels by respecting the geometrical conditions and boundary conditions already explained above.

-Assigning the plane strain boundary conditions and the initial stress state.

-*Phase 1*: The excavated ground inside the first tunnel is deactivated and a radial pressure is simultaneously applied to the tunnel boundary towards the ground medium, the value of this pressure is calculated by applying Eq.(1)

$$\sigma = (1 - \lambda)\sigma_0 \tag{1}$$

with σ(kN/m^2): radial pressure; σ_0(kN/m^2): initial stress in the ground medium and λ is the stress release ratio. The application of the final stress release ratio is done by applying a reduced radial pressure to the excavation boundary; the reduction of this pressure is done step-by-step until reaching the chosen stress release value.

-*Phase 2*: The support system is activated and a total relaxation is applied along the tunnel boundary.

-Starting the construction of the right tunnel using the same construction phases applied to the left one. Both tunnels were excavated under similar conditions, the only difference was the variation of excavation phase shift (P_s) through the variation of the stress release ratio λ_R (stress release ratio of the right tunnel). Multiple 2D calculations were performed by modifying the parameter λ_R.

5. Numerical results and discussion

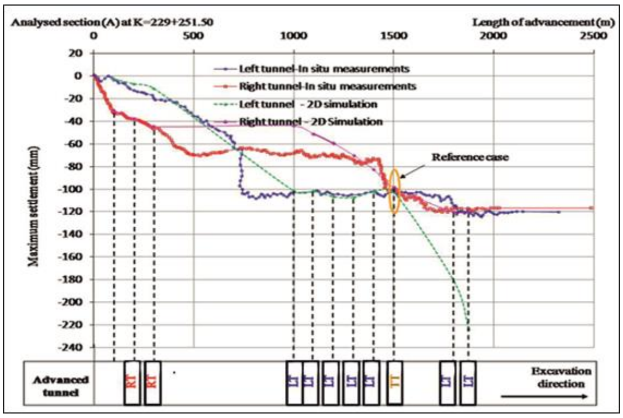
For the purpose of a numerical investigation, a λ value of 0.60 was adopted initially for the two tunnels (reference case $\lambda_L = \lambda_R$)(Fig.5(a)). The value of the stress release ratio for the left tunnel is constant, λ_L =0.60, while the stress release ratio for the right tunnel is variable (λ_R= 0.45, 0.50, 0.55, 0.60, 0.65, 0.70, 0.75). We admit that if:

• $\lambda_R=\lambda_L$=0.60 that corresponds to the reference case (the two tunnels advanced simultaneously) (Fig. 5(a)).

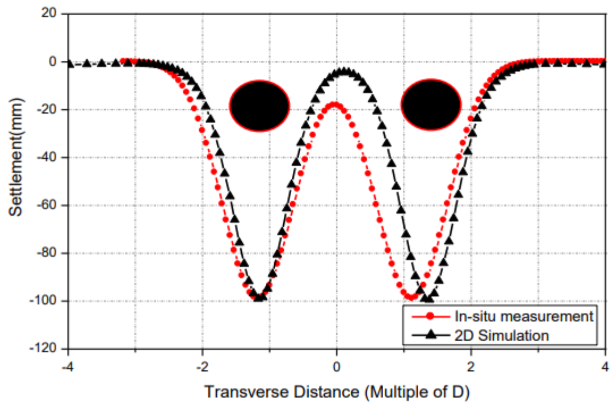
• λ_R=0.45= λ_L-0.15 that corresponds to a decrease of 25% in the values of λ_R compared to λ_L, which leads to a decrease of 25% of P_s compared to the reference case (the left tunnel is the advanced one) (see Fig. 5(b)).

• λ_R =0.75= λ_L+0.15, which corresponds to an increase of 25% in the values of λ_R which leads to an increase of 25% of P_s compared to the reference case (the right tunnel is the advanced one, Fig. 5(c)). The same approach is applied to other values of λ_R.

The stress release ratio λ_R of the right tunnel changed over a range 0.45 to 0.75 while theoretically, it can reach the unity that corresponds to a total relaxation. However, for λ>0.75, during the numerical analysis, the model could not reach an equilibrium state. The same observations were found by Do *et al.* (2014c). They attributed this result to the

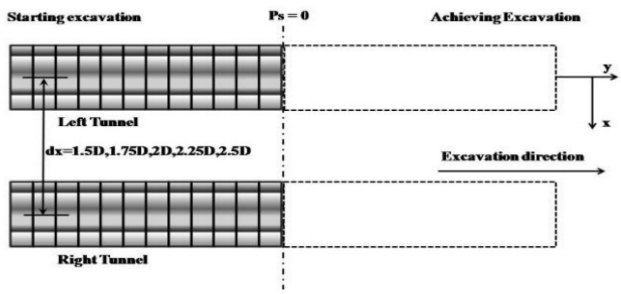


(a)

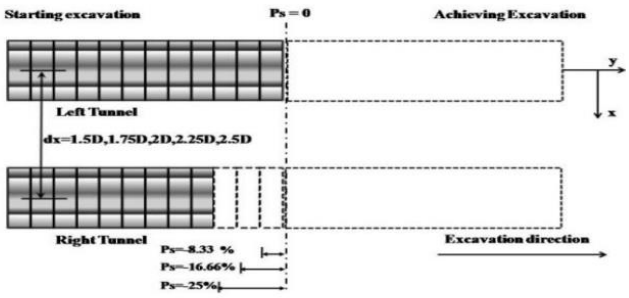


(b)

Fig. 4 (a) Longitudinal settlement profiles, a comparison between numerical simulation and in-situ measurements. (b) Settlement profile in the transverse section; comparison between numerical simulations and in-situ measurements

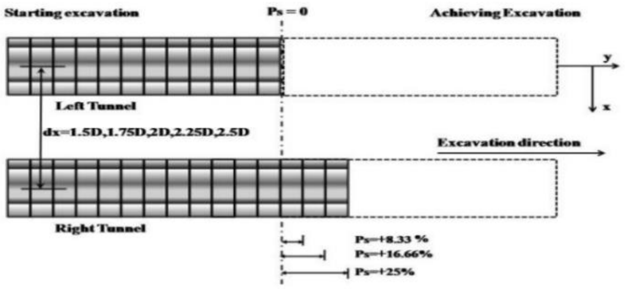


(a)



(b)

Fig. 5 (a) Plan view of the twin tunnels for the reference case (not scaled), (b) Plan view of the twin tunnels for the case1 (not scaled) and (c) Plan view of the twin tunnels for the case 2 (not scaled)



(c)

Fig. 5 Continued

nonstop failure process that occurs in the ground surrounding the tunnel.

5.1 Comparison between numerical simulation and in situ measurements

The determination of the stress release ratio is one of the difficulties when applying the CCM which, is usually determined by a comparison between 3D numerical analysis and in-situ measurements. Other Two-dimensional numerical studies using the convergence-confinement method have been done by other authors ((Lü and Low (2011), Lü *et al.* (2011), Janin (2012), Janin *et al.* (2013), Zhang and Goh (2015, 2016)). They assumed that the CCM method used in a 2D numerical studies can correctly simulate the realistic behavior of the third dimension when excavating a tunnel, but it requires a priori estimation of the stress relaxation ratio. In fact, the stress release ratio is usually defined on the basis of a back analysis that employs experimental data obtained from a tunneling process. For the current problem of interest, the stress release ratio has been estimated directly on the basis of in-situ measurements obtained by proposing a simple and effective formula without referring to the 3D numerical analysis which requires a greater number of parameters and consumes more computing time than 2D analys is does. This formula allows the stress release ratio at each transverse section along the tunnel to be calculated as a function of the advancement length of the advancing tunnel (L_{AT}) and the total length of the tunnel (L_{TT}). This estimation by Eq. (2) was performed for the advanced tunnel at a different section of the T4 tunnels of El-Harrouche Skikda in order to highlight the effect of tunnel advancement. If the advancing tunnel is shifted it will not be necessary to redo all the numerical simulations, but it will be only necessary to use the previous formula for calculating the parameter λ when applying the CCM.

$$\lambda = \frac{L_{AT}}{L_{TT}} \tag{2}$$

As the determination of λ is a perplexing problem, this seems to be a promessing way of addressing the excavation phase shift factor in a 2D numerical simulation.

In this study, the ability of the 2D approach to represent the real in-situ measurements was examined as well. For this purpose, the results from in-situ measurements are compared with those of several 2D numerical simulations previously carried out in FLAC2D.

As shown in Fig. 4(b) for $\lambda_L = \lambda_R = 0.60$, which has been adopted in this paper as a reference case, the matching between 2D numerical results and the in-situ measurements was satisfactory. Consequently, the 2D model is validated and we applied the following analysis.

5.2 Cases of study

In all cases, the left tunnel is constructed first. In the reference case (Fig. 5(a)) the double tunnel faces advanced simultaneously (P_s=0).

Case 1: In the first case (Fig. 5(b)) the left tunnel is the advanced one, with decreasing the excavation phase shift (P_s) of -8.33%, -16.66% and -25% compared to the reference case.

Case 2: In the second case (Fig.5(c)), the right tunnel is the advanced one, with increasing the excavation phase shift (P_s) of +8.33%, +16.66%, and +25% compared to the reference case.

6. Discussion

Fig. 6 shows the settlement troughs above the twin tunnels for various horizontal distances, d_x (d_x=1.5*D*, 1.75*D*, 2*D*, 2.25*D*, and 2.5*D*) and P_s=0, d_x=2.5*D* corresponds to the real reference case (Fig. 4(b)). For ease of comparison, the settlement trough over a single tunnel (left tunnel) is also presented. As assumed both the maximum settlement and amplitude depend on the distance between tunnels, it can be seen that the excavation of a second tunnel (right tunnel) near the first one (left tunnel) leads to an increase in the surface settlement. This can be explained by the accumulated loss of the ground in both tunnels ((Do *et al*. 2013a, Fang *et al*. 2016)).

When the tunnel spacing ratio d_x/D increases the settlement trough over the twin tunnels becomes shallower and wider. The maximum soil settlement is observed for the configuration of a closed tunnel (d_x=1.5*D*), this result is in good agreement with results of Chehade and Shahrour (2008) obtained by their 2D numerical analysis. For a

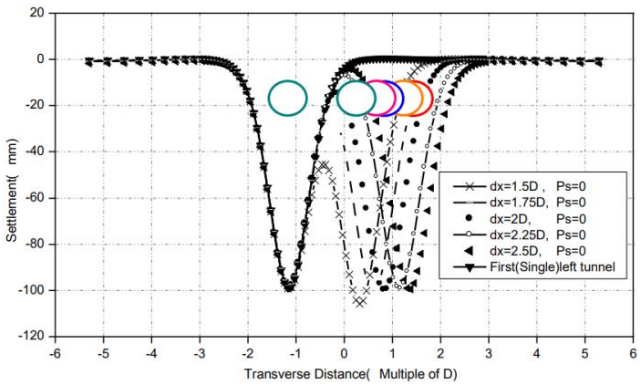


Fig. 6 Settlement troughs above the twin tunnels at various horizontal distances (d_x), for the reference case (P_s=0) (*D* is the tunnel diameter in meter)

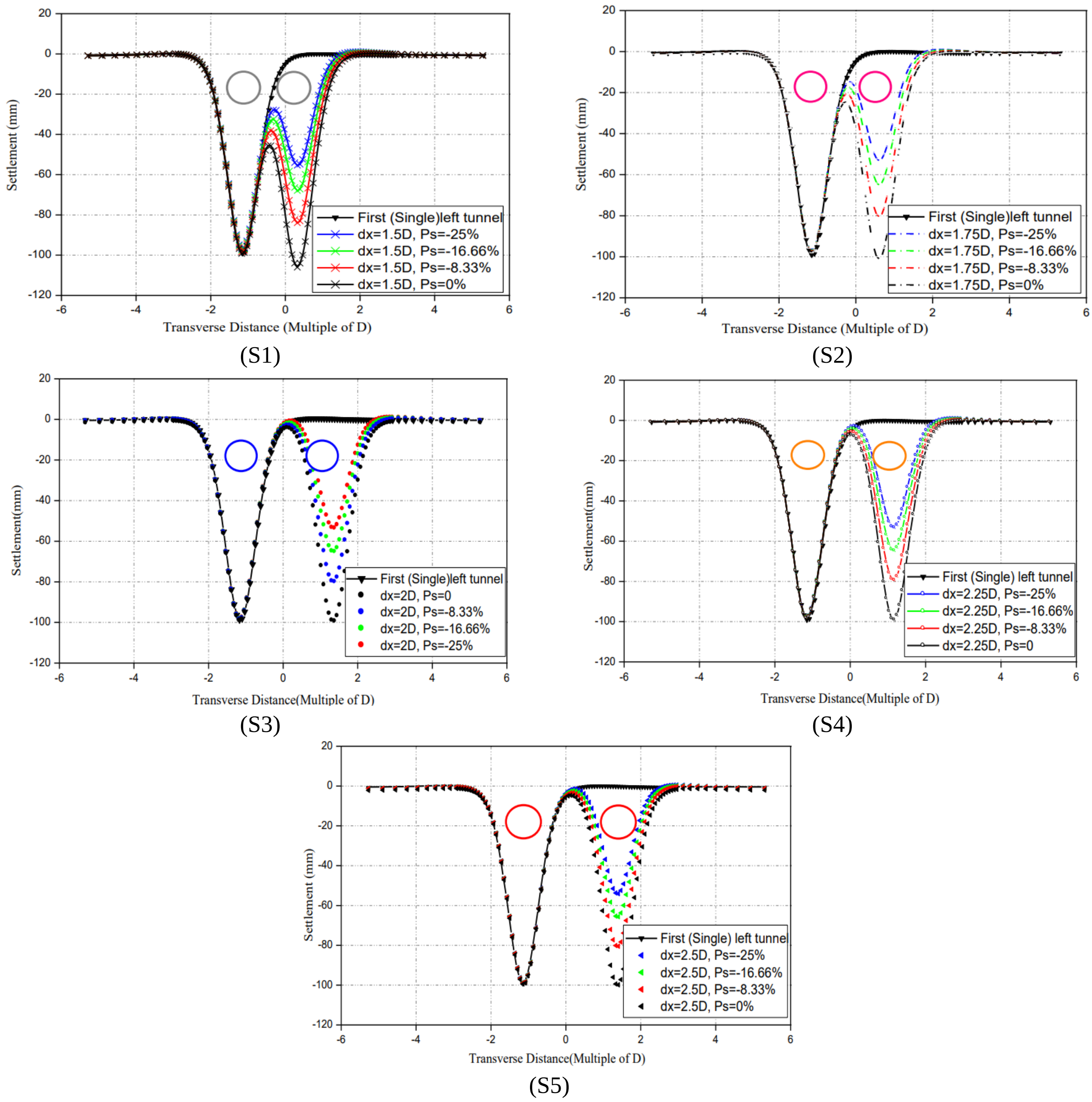


Fig. 7 Settlement troughs above the twin tunnels for various horizontal distances with decreasing P_s of -8.33%, -16.66% and -25% compared to the reference case

simultaneous advancement of the twin tunnels (P_s=0), when tunnel distance d_x reaches 2D the value of the maximum settlement gets very close to that of a single tunnel, this conclusion is similar to that found by Wang *et al.* (2017), Addenbrooke and Potts (2001), While the settlement in the central point between the two tunnels was relatively small, this finding agrees with the results of Choi and Lee (2010), Fang *et al.* (2016).

When d_x increases the shape of the settlement trough is more symmetrical above the two tunnels (Fig.6). Similar conclusions were obtained by Chehade and Shahrour (2008), Hasanpour *et al.* (2012), Mirhabibi *et al.* (2012), Choi and Lee (2010).

a) The left tunnel is the advancing one (case 1)

The great influence of the continuous advancement of the left tunnel through the decrease of the excavation phase shift distance (P_s) compared to the reference case (Fig.4(b)) on the ground deformation can be seen in Fig.7. The findings from the numerical analyses, a summary of which is presented in Fig. 7 are listed as follows:

-With a decrease of P_s the general shape of the settlement trough takes the form of a grouping of two left-right adjacent troughs.

-Decreasing the excavation phase shift distance between the two tunnels results in the same tendency for the first left trough as that predicted for the simultaneous advancement of the two tunnels (reference case).

-Concerning the distance between tunnel center lines (d_x), for d_x=1.5D as an example, as the excavation phase shift decreases, that is, the left tunnel is the advancing one, the maximum settlement on top of the left tube remains almost constant while the maximum settlement on the right

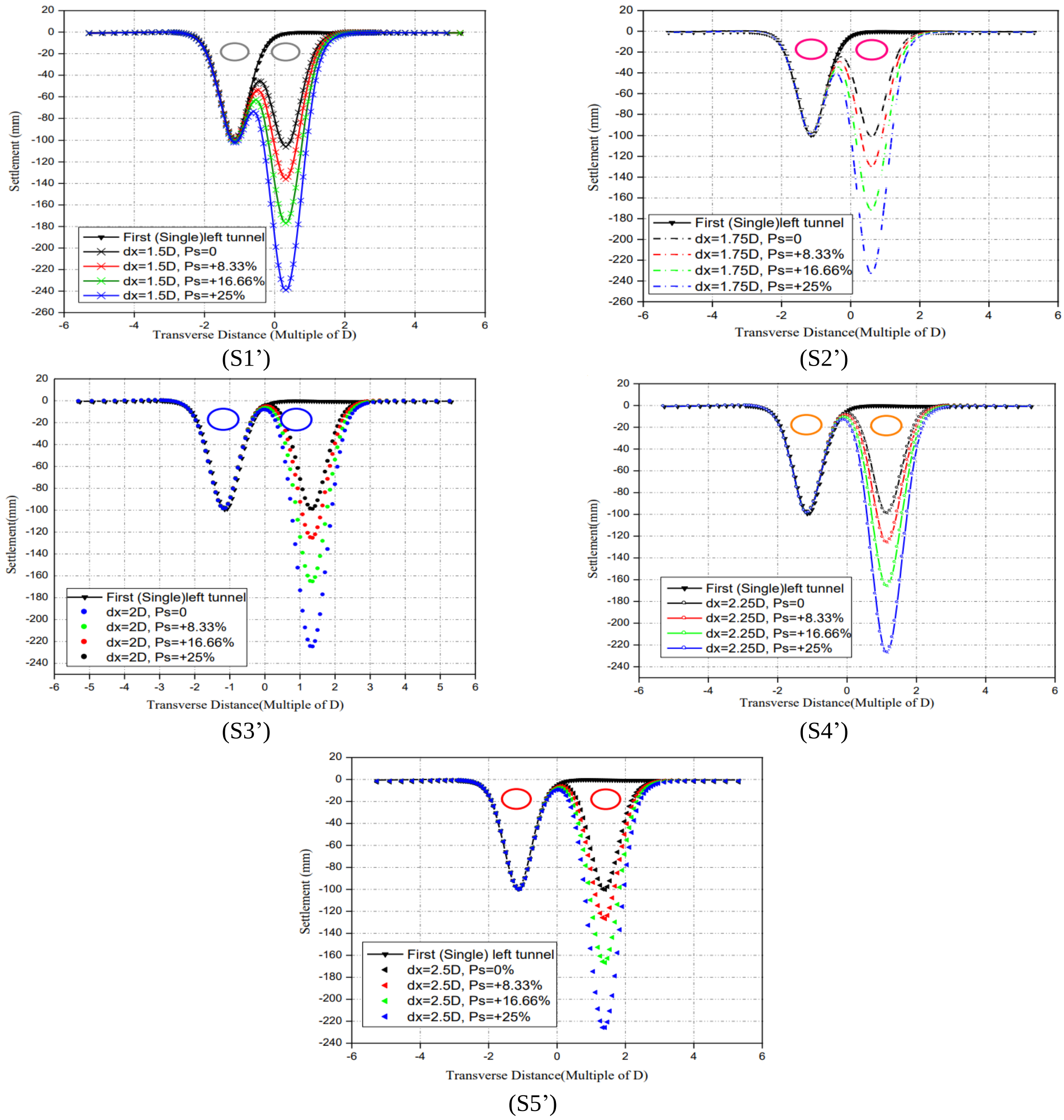


Fig. 8 Settlement troughs above the twin tunnels for various horizontal distances with increasing P_s of +8.33%, +16.66% and 25% compared to the reference case

one increases with the decreasing phase shift. This outcome is also valid for the other four cases of d_x.

-It is observed also in Figs. 7 and 8 that when distance 'dx' between tunnels increases the settlement in the middle between the left and right tunnels tends to 0.

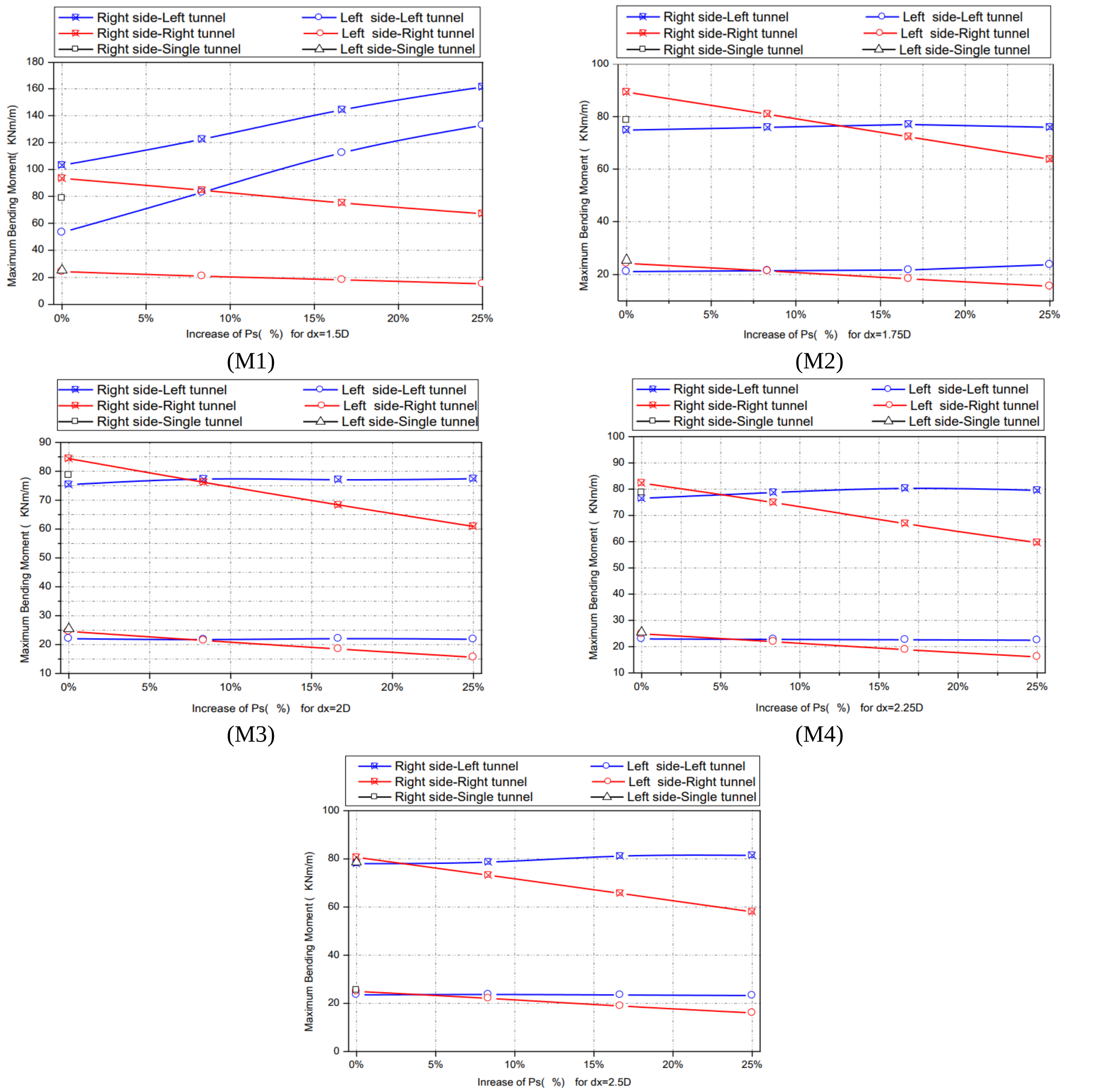
-Regarding the excavation phase shift (P_s), when the P_s parameter is taken as constant, the maximum settlement on both tunnels decreases as d_x increases.

-Decreasing the excavation phase shift distance between the two tunnels results in the same tendency for the first left trough as that predicted for the simultaneous advancement of the two tunnels (reference case), where the maximum settlement becomes steady.

-However, the maximum settlement above the right tunnel decreases sharply as P_s decreases and the maximum value of the settlement will be above the tunnel constructed first (left tunnel).

-The greatest surface settlement is observed when the two tunnels are excavated simultaneously (P_s=0); a similar observation of smaller surface settlements developed above the following tunnel was also obtained from our field measurement (Fig.4(a)) and from those introduced by Chen *et al*. (2011), as well as through the 3D numerical simulation carried by Do *et al*. (2014a, 2016).

-In other words, the settlement trough above the twin tunnels calculated after the excavation of the right tunnel seems to depend, to a large extent, on the increasingly decrease of P_s (Fig.7). Instead, it can be associated with the fact that the failure zone close to the right tunnel becomes not significant as P_s decreases. In this, the downward movement above the right tunnel decreases when P_s decreases. This may be because the right tunnel is



(M1) (M2) (M3) (M4) (M5)

Fig. 9 Variation of bending moment (kN·m) in lining with decreasing P_s of -8.33%, -16.66% and -25% compared to the reference case

excavated in a soil zone which was first greatly disturbed by the excavation of the first tunnel (left tunnel) with a λ_L larger than λ_R. Consequently, a significant part of the disturbed soil adjacent to the second tunnel has taken place before the excavation of the right tunnel. Thus, the downward movement of soil caused by the right tunnel is reduced. Similar conclusions were found by Fang *et al.* (2016).

b) The Right tunnel is the advancing one (case 2)

Fig. 8 shows the surface settlement developed above the twin tunnels, with an increasing advancement of the right tunnel (increasing P_s). The reference case (P_s=0) is also presented for comparison.

The findings from the numerical analyses, a summary of which is presented in Fig.8, are listed as follows:

-The value of δ_{max} for the right tunnel is severely affected by the changes with both d_x and P_s.

-The increasingly advancement of the right tunnel (Fig. 8) results in the same tendency for the first left trough as that predicted when the twin tunnels are simultaneously excavated (reference case; P_s=0), similar field observation results were found by Chen *et al.* (2011) and He *et al.* (2012) during the excavation of twin tunnels in silty and sandy soil respectively.

-The surface settlement above the right tunnel seems to depend to a large extent on the increase of P_s; the greatest surface settlement is observed when the right tunnel is excavated with a P_s distance equal to +25% compared to the reference case when the double faces of the twin tunnels advanced simultaneously. It can instead be associated with

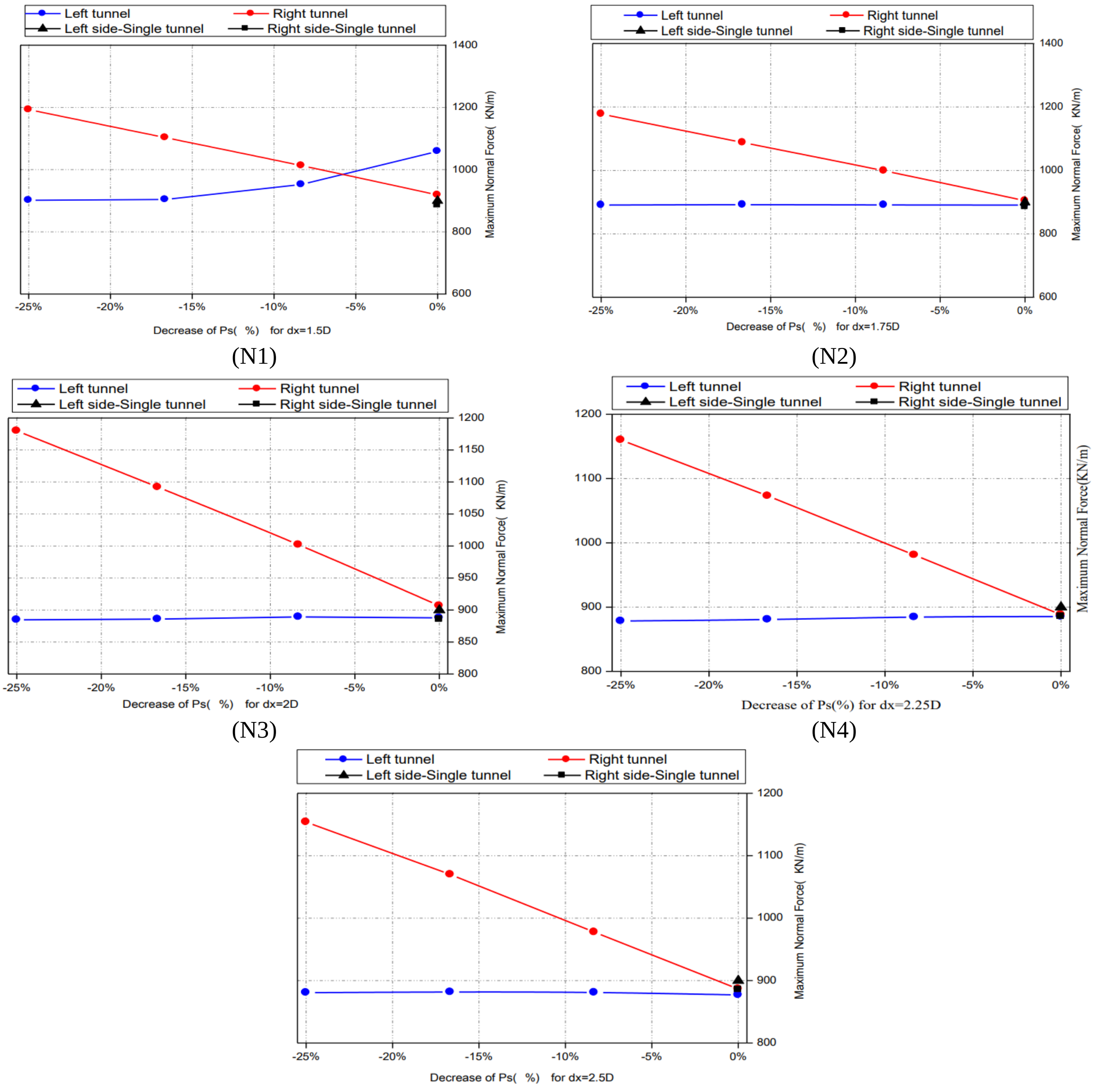


Fig. 10 Variation of normal forces (kN/m) in lining with decreasing P_s of -8.33%, -16.66% and -25% compared to the reference case

the fact that the failure zone close to the right tunnel becomes more significant as P_s increases.

This phenomenon could be attributed to augmentation of λ_R of the right tunnel which causes large lateral movements of the soil in the zone between the two tunnels and particularly in the zone around this excavation and is followed by large downward movements of the soil above the right tunnel this result is in good concordance with the results of Do *et al*. (2016), Addenbrooke and Potts (2001).

-It is also interesting to note that when P_s increases the shape of the settlement trough becomes more asymmetrical above the two tunnels.

-The maximum value of settlement above the right tunnel increases as P_s increases (Fig. 8).

c) Internal forces in the tunnel lining (case 1)

Fig. 9 shows the maximum absolute value of the bending moment in the lining of both the left and right tunnels for P_s=0 and various horizontal distances d_x (d_x=1.5*D*, 1.75*D*, 2*D*, 2.25*D*, and 2.5*D*) where d_x=2.5*D* corresponds to the real reference case. In addition, the maximum absolute value of bending moment from a single tunnel (left tunnel) is shown for comparison. We conclude that:

-The maximum absolute value of bending moment is affected by both d_x and P_s. As d_x is taken constant, the value of M_{max} on the left side of the left tunnel remains about the same while it decreases slightly on the right side of the left tunnel as P_s decreases.

-The M_{max} is greater on the right side of the left tunnel than it is on the left side. This outcome is the same for the right tunnel.

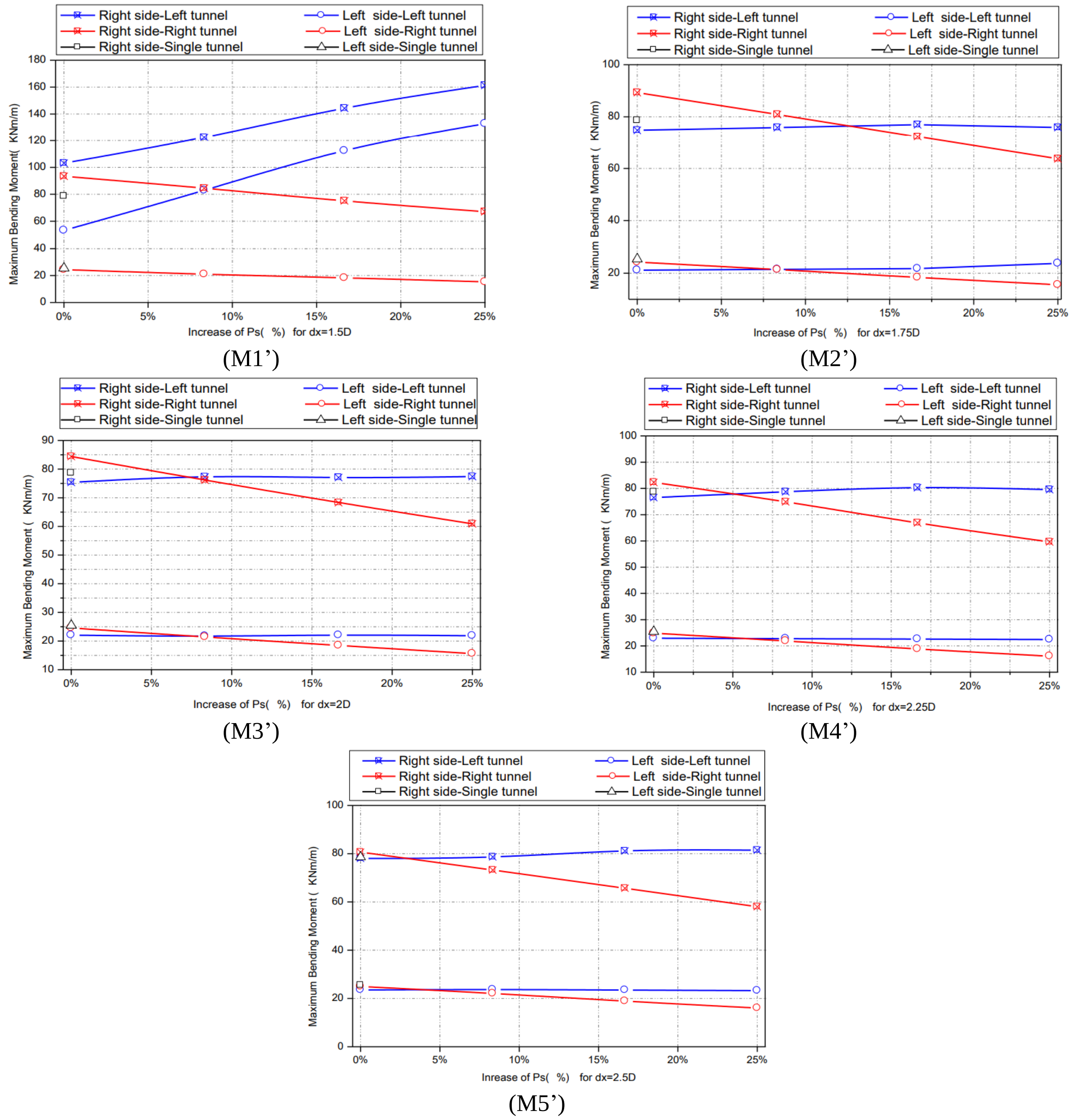


Fig. 11 Variation of bending moment (kN·m) in lining with increasing P_s of +8.33%, +16.66% and +25% compared to the reference case

-When d_x=2*D* (Fig. 9(M3)) all values of M_{Max} gain about constant value. If d_x>2*D* the interaction between two tunnels decreases in terms of M_{Max}.

-For d_x=1.5*D* and with P_s=0 (Fig. 9(M1)) the magnitude of the bending moments is greater in the left tunnel than in the right tunnel. This suggests that the first tunnel (left tunnel) carries a larger portion of load than the second tunnel (right tunnel) because it is constructed first.

-The maximum bending moment occurs on the right side of the left tunnel. These conclusions are in good agreement with the results of Do *et al*. (2014a).

-For d_x=1.5*D* when the twin tunnels are excavated simultaneously (P_s=0) an important difference in the maximum absolute value of the bending moment induced in two tunnels can be observed.

-It can be seen in Fig. 9 that the excavation of the right tunnel causes important changes in the maximum absolute value of the bending moment, this finding agrees with the conclusion of Addenbrooke and Potts (2001). We find an increase in the maximum absolute value of the bending moment in the pillar spring line region, particularly at the left side of the left tunnel. This is consistent with the results of Ng *et al*. (2004) and Kim *et al.* (1998), who reported that the incremental bending moment of the first tunnel is largest at the pillar spring line regions near the left tunnel.

-When d_x reaches 2*D* for P_s=0 (Figs. 9(M3), 9(M4), and 9(M5)) we find a strong resemblance between the maximum absolute value of the bending moment in the first tunnel (left tunnel) and the single tunnel. This could be attributed to the fact that the first tunnel behaves as a single tunnel, due to the large d_x. This may be also one of the main reasons for a similar settlement trough observed above the

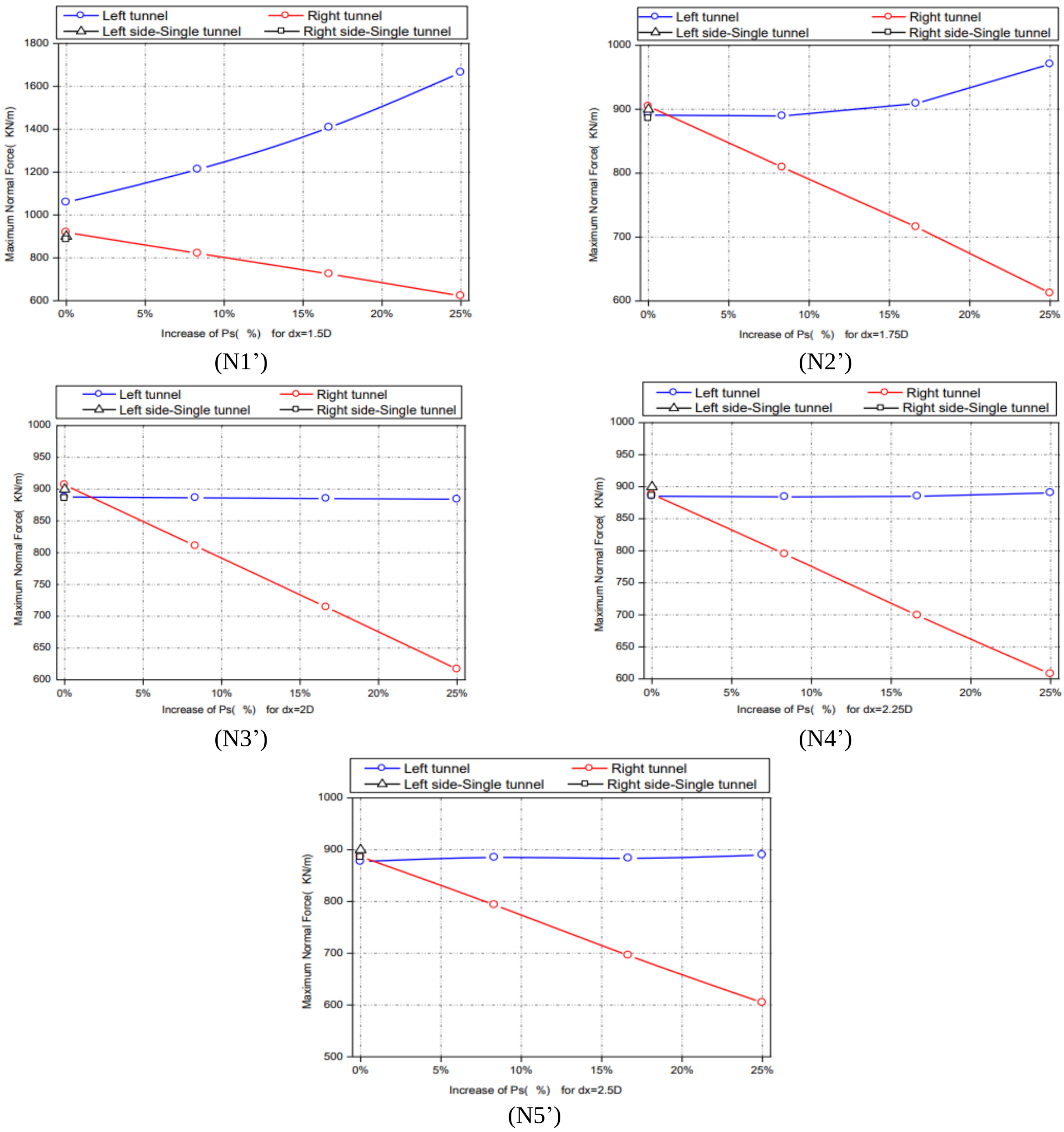


Fig. 12 Variation of normal forces (kN/m)in lining with increasing P_s of +8.33%,+16.66% and +25% compared to the reference case

single and left tunnel for larger d_x values. However, when d_x reached 2*D*, which is quite large for P_s=0, the maximum absolute value of the bending moment becomes the same for both left and right tunnels suggesting equal sharing of loads between the two tunnels when d_x reaches 2*D* (Figs. 9(M3), 9(M4), and 9(M5)), these observations are consistent with the results of Ng *et al.* (2004) who reported that for no lagging distance between the twin tunnels excavated faces, the maximum incremental bending moment is the same for the twin tunnels, Indeed, the works conducted by Do *et al.* (2014b, d) reveal that when the distance between tunnels axis reached 2D, the interaction between them can be ignored.

-For the right tunnel, the value of M_{max} increases as P_s decreases for both sides. These findings are similar for the other four cases of d_x.

-With a decrease of P_s for different d_x values (Fig.9) the maximum absolute value of the bending moment in the lining of the left tunnel decreases, while this value in the lining of the right tunnel increases.

-When d_x reaches 1.75*D* (Figs. 9(M2), 9(M3), 9(M4), and 9(M5)) as P_S decreases, there is a transfer of load from the first tunnel (on the left) to the second tunnel on the right, leading to a decrease of the maximum bending moment in the left tunnel and an increase in the maximum bending moment in the right tunnel.

-On the other hand, the bending moment in the lining of the right tunnel which increases up to 46% compared with the reference case will require more structural capacity and reinforcement.

-When the value of d_x is small, the interaction between two tubes gets more significant in terms of bending moments, which decreases with respect to the reference case (P_s=0).

-The bending moment was compared only to the left and right side of each tunnel because we found that the influence of P_s at other locations around the two tunnels opening are relatively insignificant.

-For different d_x values (Fig. 9), the increase in bending moment induced in the right tunnel lining could be attributed to the movement of the ground at the region between the two tunnels (Do *et al*. 2014a) from the left tunnel to the right tunnel due to the continuous advancement of the left tunnel (negative decrease of P_s; see Fig.5(b)).

Normal forces in tunnels linings with a continuous advancement of the left tunnel (negative decrease of P_s) are shown in Fig.10.

-The maximum normal forces on the right tunnel are greater than they are on the left tunnel under the same d_x and P_s conditions. It appears that the max normal forces are not affected significantly by the variation of either d_x or P_s.

-For d_x=1.5*D* the decrease of P_s (Fig.10(N1)) provided normal forces in the right tunnel that is generally higher than those obtained for the left tunnel. When d_x reached 1.75*D* (Figs. 10(N2), 10(N3), 10(N4), and 10(N5)) the deformation pattern is dominated by an increase in the normal force in the right tunnel and an approximate stabilization in the maximum normal force in the left tunnel. These results confirm previous vertical settlements above the left tunnel, where the maximum settlement trough above the left tunnel is steady even if the left tunnel is increasingly advanced (P_s decreases).

-Also when d_x reached 1.75*D* for P_s=0 the equal and smallest incremental normal forces are calculated for the two tunnels.

-When P_s=0 the normal forces on both tunnels become about the same and they are not affected by the change of d_x.

-It can be seen that the influence of the decrease of P_s on the normal force is more significant at the right tunnel, the determined variation of the axial force with a decrease of P_s are compatible with the bending moment results shown in Fig.10.

d) Internal forces in the tunnel lining (case 2)

-For different d_x values when the right tunnel is increasingly advanced (positive increase of P_s) (Fig.11) there is a transfer of load from the right tunnel to the left tunnel that led to an increase in the maximum absolute value of the bending moment measured in the left tunnel and a decrease in this value in the right tunnel.

-It is interesting to note that with an increase of P_s for d_x=1.5D (Fig.11(M1')), the lining of the left tunnel attracted more load and will require more capacity with greater thickness as P_s increases, these agree with the results of Tafraouti *et al*. (2016).

-However, when d_x reaches 1.75*D* the lining of the left tunnel could be thinner with less reinforcing (Figs.11(M2'), 11(M3'), 11(M4'), and 11(M5')).

-For the two cases when d_x=1.5*D* (Figs.9(M1) and 11(M1')) the variation of the excavation phase shift (P_s) of the right tunnel has a strong effect in bending moment on the lining of the left tunnel particularly on the right side of this tunnel.

-When tunnels distance centers d_x reach 2*D* as shown in Figs. 9(M3) and 11(M3') the maximum absolute values of the bending moment are approximately similar in both tunnels. The maximum absolute value of the bending moment of the two tunnels is largest in the region between the two tunnels at the right side of the left tunnel near the right tunnel these agree with the results of Kim *et al*. (1998) and Do *et al*. (2014a).

-During the simultaneous advancement of the double tunnel faces (see Figs. 9 and 11) for the two cases as the tunnel distance centers are lower than 1.75*D* the bending moment in the left tunnel is greater than that in the right tunnel. On the contrary, when P_s=0 beyond the tunnel centers distance of 1.75*D* the bending moment on the right tunnel lining is greater than that in the left one. This is consistent with the numerical results performed by Do *et al*. (2014b).

-For P_s=0 when d_x reaches 2*D* and spatially for d_x=2.5*D* (Figs. 9(M4), 9(M5), 11(M4') and 11(M5')) the maximum bending moment is the same for both left and right tunnels where the loads are distributed equally between the two tunnels.

-As shown in Fig.11, the increasing advancement of the right tunnel (a positive increase of P_s (Fig. 5(c)) would result in a reduction in the maximum absolute value of the bending moment in the right tunnel and an increase in this value in the left tunnel.

We suggest that the lining of the right tunnel is subjected to an unloading mechanism which increases as P_s increases. In the case 2 (inversed case), when the right tunnel is the advancing one (increasing P_s) for d_x=1.5*D* (Fig.12(N1')), as P_S increases there is a maximum increase of 105% and 421% in the maximum normal forces induced respectively in the right and left side of the left tunnel compared to the reference case and a decrease of the maximum normal forces of 14% and 39%, respectively, in the right and left side of the right tunnel. These results are compatible with the suggestion of the presence of a transfer charges mechanisms between the twin tunnels and the results of bending moment shown previously in Fig. 11(M1').

-However, for P_s=0 when d_x reached 2*D* (Figs.12(N3'), 12(N4'), and 12(N5')) the maximum normal forces obtained in the two tunnels is more similar in magnitude to those determined in a single tunnel.

-Figs. 12 (N1', N2') show that the smallest normal forces in the left tunnel for d_x=1.5*D* and 1.75*D* are obtained during the simultaneous advancement of the two tunnel faces (P_s=0).

In this case, the maximal forces are similar to those induced in the case of a single tunnel, these results agree with Do *et al*. (2016).

-However, the advancing process of the right tunnel causes a continuous decrease in the normal forces induced in the right tunnel and an approximate stabilization (usually a very slight increase) of the normal forces in the left tunnel (Fig.12). This could be attributed to the fact that the right tunnel was excavated when the lining in the left tunnel has reached a steady state (Do *et al*. 2016) due to the constant value of the stress release ratio λ_L=0.60 while the structural forces in the right tunnel in the measured section are still changing as P_s increases. These conclusions are in good agreement with the work made by Liu *et al*. (2008) they pointed that when the face of the second tunnel is far from the first, the second tunnel has less effect on the support system of the first one.

-The decrease of the normal forces induced in the right tunnel could be explained by the movement of soil from the zone around the right tunnel towards the soil between the two tunnels. Consequently, the normal forces measured in the advanced tunnel (right tunnel) are lower than those induced in a single tunnel as P_s increases. Some results close to the latter were found by Do *et al*. (2014a) who pointed out that when the face of the second tunnel is far from the first, the second tunnel has less effect on the support system of the first one, they also revealed that the excavation of twin tunnels can cause smaller structural forces, accompanied by a higher settlement above the two tunnels.

7. Conclusions

The equivalent 2D analyses presented in this investigation by introducing the excavation phase shift factor and the simple determination of the stress release provide an insight into the real interaction effect of twin tunnel construction and are ready to be used as a preliminary result or reference for more sophisticated predictions and evaluations in tunnel design. The interaction between the two tunnels was assessed, the results from the modeling using the new approach were compared with the in-situ measurements. It is also possible to draw the following conclusions:

• The excavation of a second (right) tunnel has a strong effect on the behavior of the existing one (single tunnel).

• The horizontal distance between the two tunnels axis affects the soil settlement and structural forces in the lining.

• The excavation of a second tunnel causes an increase in the surface settlement compared to that of a single tunnel.

• For a large horizontal tunnel distance (d_x) the first tunnel behaves as a single tunnel.

• The critical distance d_x between two tunnel centers in terms of the lining stability is equal to 1.5*D*.

• The settlement trough above the twin tunnels is strongly affected by excavation phase shift distance.

• The highest soil settlement trough is obtained when the right tunnel is the advanced one.

• The variation of excavation phase shift of the right tunnel results in the same tendency for the first left trough as that predicted for the simultaneous excavation of the twin tunnels (reference case).

• When the left tunnel is advanced ahead, the lining of the right tunnel will require more structural capacity and reinforcement.

• When the right tunnel is advanced ahead, for d_x=1.5*D*, the lining of the left tunnel will require more capacity as P_s increases. However, when d_x reached 1.75D the lining of the left tunnel could be thinner with less reinforcing.

• The load transfer mechanism between the two tunnels is greatly influenced by the variation of excavation phase shift.

• Quantitatively, this work shows that the proper choice of excavation phase shift for the second tunnel significantly decreases the soil movement caused by double excavation.

• The choice of the excavation phase shift must be taken into account during the design phase of a project.

This paper has proposed the application of the confinement convergence method to the case of two tunnels with offset, by means of a mixed numerical and empirical approach. The method has been validated through a comparison with real measurements. It is important to remember that the method is numerically much more economical than the 3D calculation, this present a practicalutility, in addition, it is an extension to conventional confinement convergence method which represents the main originality. In the future related research, the applicability of the new approach in other real projects, as well as a comparison with 3D numerical simulation by introducing the excavation phase shift factor will be carried out.

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