Effects of geometrical conditions and construction sequence on the ground settlement and internal forces of twin tunnels

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ABSTRACT
In this paper, the effects of relative position and depth of twin tunnels on the values of ground settlement and internal forces developed in the tunnel lining are investigated. Also, the effect of construction sequence is studied. Numerical models and analyses conducted for horizontally-aligned and vertically-aligned twin tunnels are presented. It is concluded that higher ground settlement and internal forces are developed for the vertically-aligned tunnels especially when the upper tunnel is constructed first.

RÉSUMÉ
En ce document, les effets de la position relative et la profondeur des tunnels jumeaux sur les valeurs du règlement au sol et des forces internes développés dans la doublure de tunnel sont étudiés. En outre, l'effet de l'ordre de construction est étudié. Des modèles numériques et les analyses conduits pour les tunnels jumeaux horizontal-alignés et vertical-alignés sont présentés. On le conclut que le règlement d'éminence et les forces internes sont développés pour les tunnels vertical-alignés particulièrement quand le tunnel supérieur est construit d'abord.

1 INTRUDUCTION

The development of transportation in large cities requires the construction of new tunnels close to the existing ones. The use of twin tunnels has some advantages compared to the use of a single tunnel with bigger cross section. The volume of excavated materials, the influence range, the soil movement and the requierd techniques for construction of a tunnel with a bigger cross section would be much greater than the construction of twin tunnels.

Both numerical modeling and in situ observations have been used to analyze the interaction between twin-tunnels (Soliman et al., 1993; Kawata and Ohtuska, 1993; Perri, 1994; Saitoh et al., 1994; Yamaguchi et al., 1998; Shahrour and Mroueh, 1997). Results show that in some configurations, the interaction could largely affect the soil settlement and that the design of twin tunnels requires numerical analysis associated with the monitoring during the tunnel construction.

Since the relative position, construction sequence and overburden of twin-tunnels, affect the soil settlement and tunnels internal forces, this paper presents analysis of this issue with a particular interest for the optimization of the relative position, construction sequence and overburden of twin-tunnels. This paper presents numerical models and analyses conducted for two configurations of twin-tunnels: horizontally-aligned and vertically-aligned tunnels (Figure 1 and 2).

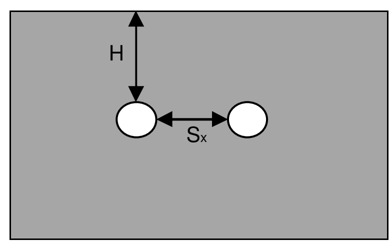

Figure 1. Tunnels with horizontal alignment

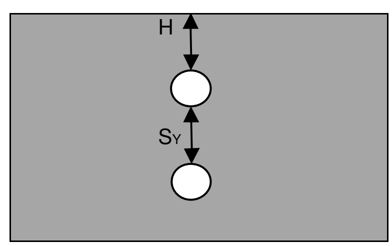

Figure 2. Tunnels with vertical alignment

2 NUMERICAL MODELING AND PARAMETER SELECTION

2.1 Numerical Modeling

The numerical analysis tool adopted in this study is the finite element program PLAXIS Ver. 8. The two-dimensional plane stress model was carried out for a mesh block and the ground is described with 15-noded wedge elements. The soil behaviour is described using an elastic perfectly plastic constitutive relation based on the non associated Mohr-Coulomb criterion. The behaviour of the lining is assumed to be linear-elastic.
To ensure the absence of lateral boundary effect on the numerical modeling of the tunnel construction, the center of each tunnel to the vertical and horizontal boundaries is taken as 5.5 times the radius of the tunnel. Concerning the boundary conditions, the displacements are constrained in both directions at the bottom, while zero horizontal displacement is imposed at lateral boundaries (Figure. 3).

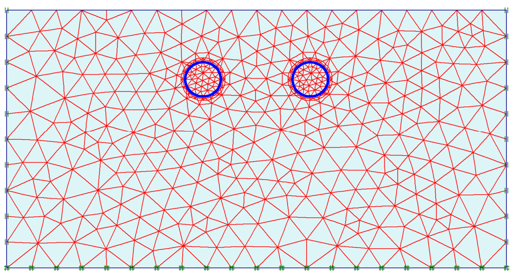

Figure 3. Mesh used in the analysis of twin tunnels with horizontal alignment

The finite element modelling of the construction of twin-tunnels is carried out as follows:

If the twin tunnels are excavated simultaneously:

Construction of both tunnels using the convergence-confinement method with a stress release factor β=0.4. This factor corresponds to the ratio of the stress release before the lining installation.

If there is a time lag between the construction of twin-tunnels:

(i) Construction of the first tunnel using the convergence-confinement method with a stress release factor β=0.4.

(ii) Construction of the second tunnel using also the convergence-confinement method, as for the first tunnel with a stress release factor β=0.4.This factor is applied to the stresses exercised around the tunnel after the excavation of the first tunnel.

2.2 Material Parameters

The parameters adopted in this study were mainly derived from field geological investigations and back analysis of tunnel monitoring data during excavation of Resalat twin tunnels in Tehran. Soil parameters are listed in Table 1. The sprayed concrete lining is considered with a unit weight of γ= 24 kN/m^3, a thickness of 20cm, a normal stiffness of EA= 5.2 E+6 kN/m, a flexural rigidity of EI=1.73 E+4 kNm^2/m.

Table 1. Properties of the soil

E (kPa)	Poison's ratio	Cohesion (kPa)	Friction angle[°]	K_0	γ (kN/m^3)
130000	0.3	34	40	0.5	18

3 Results of the Analyses

It is assumed that there are base conditions for pillar width and overburden of twin-tunnels (Table 2). For each configuration, effects of pillar width and overburden of twin-tunnels are considered separately and then the results of staged construction and simultaneous construction are compared. Analyses are conducted for the following configurations (Table 3):

-tunnels with horizontal alignment
-tunnels with vertical alignment

Table 2. Base conditions for pillar width and overburden of twin tunnels (D=10m)

Configuration	S_x/D	S_y/D	H/D
Horizontal alignment	1	0	1.5
Vertical alignment	0	1	1.5

Table 3. Configuration of twin tunnels analyzed in this paper (D=10m)

Configuration	S_x/D	S_y/D	H/D
Horizontal alignment	0.5,1,2,3	0	1.5,3,6
Vertical alignment	0	1,2,3	1.5,3,6

3.1 Effects of Pillar Width in Tunnels with Horizontal Alignment in the Staged Construction

Figure 4a shows the tunnel configuration considered in this section. Analyses were conducted for four values of the tunnel distance ratios S_x/D (0.5,1,2 and 3). The tunnels crown is located at 1.5D below the soil surface. In staged construction, it is assumed that the tunnel at the right is excavated first, and then the tunnel at the left is excavated. Results are presented at the completion of the construction of tunnels. Figure 4b shows the settlement at the soil surface at the end of the construction of the second tunnel. It shows that both the settlement pattern and amplitude depend on the distance between tunnels. The maximum soil settlement is observed for the configuration with close tunnels (S_x/D=0.5). In this case, the maximum soil settlement occurs between the two tunnels with a maximum value of 7 mm. The increase in the distance between tunnels results in a decrease in the settlement in the central part of the twin. Beyond the distance (S_x=D), the construction of the first tunnel does not affect the second one.

Figure 4c and 4d show the distribution of bending moment and thrust in the right tunnel. As expected, the increase in the distance between tunnels causes a decrease in the bending moment and thrust in the right tunnel. Beyond the distance (S_x=D), the construction of the first tunnel does not affect the second one.

3.2 Comparison between Simultaneous Construction and Staged Construction (Influence of the Construction Sequence and Pillar Width between Horizontal Tunnels)

Figure 5 shows the maximum settlement at the soil surface, maximum bending moment and thrust in the horizontal tunnels lining at the end of construction, in simultaneous and staged construction for four values of the tunnel distance ratio S_x/D (1.5, 2, 3 and 4). Figure 5a shows that the maximum settlement at the soil surface is about 9.5 mm in (S_x/D=0.5) in simultaneous construction. As shown in Figure 5b and 5c the maximum bending moment and thrust are about 7.5 kNm/m and -820 kN/m in (S_x/D=0.5) in the right tunnel of staged construction. As expected, the increase in the distance between tunnels results in a decrease in the difference between simultaneous and staged construction. Figure 5 shows beyond the distance (S_x=D), there is not much difference between simultaneous and staged construction.

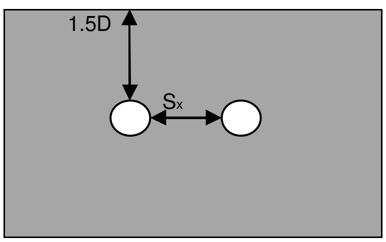

Figure 4a. Geometric configuration

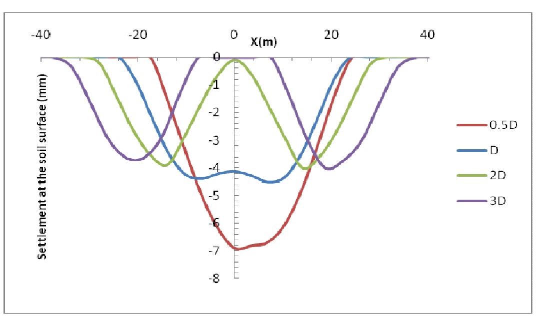

Figure 4b. Ground settlement

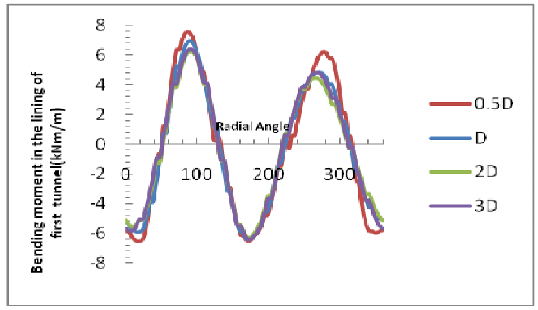

Figure 4c. Bending moment in the right tunnel

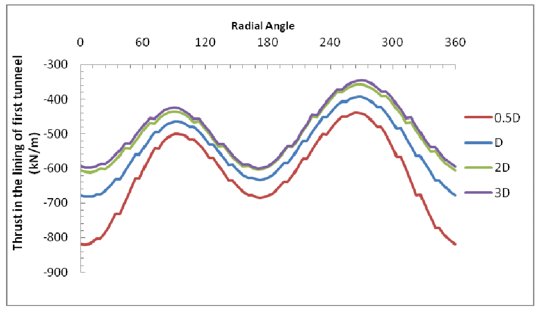

Figure 4d. Thrust in the right tunnel

Figure 4. Tunnels with horizontal alignment: influence of staged construction and distance between tunnels on the ground settlement and internal forces of first tunnel after construction of the second tunnel

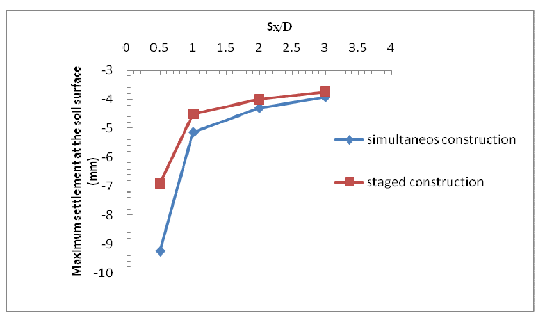

Figure 5a. Maximum ground settlement

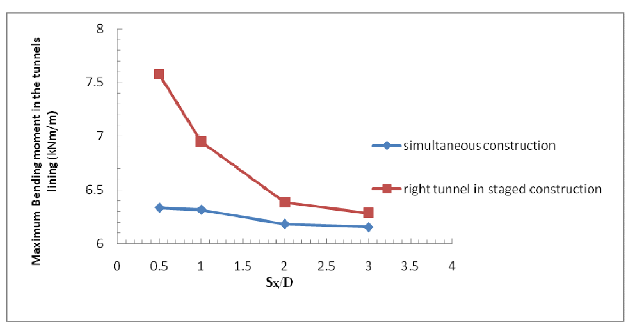

Figure 5b. Maximum bending moment in the tunnels lining

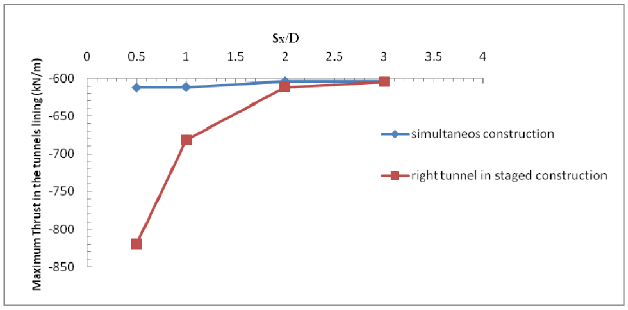

Figure 5c. Maximum thrust in the tunnels lining

Figure 5. Tunnels with horizontal alignment: comparison between simultaneous and staged construction- influence of the construction sequence and distance between tunnels on the maximum soil settlement and internal forces after construction of tunnels

3.3 Effects of Overburden in Tunnels with Horizontal Alignment in Staged Construction

Figure 6a shows the tunnel configuration considered in this section. Analyses were conducted for three values of the overburden of twin tunnels H/D (1.5, 3 and 6). Tunnels pillar width is considered D. Figure 6b shows that both the settlement pattern and amplitude depend on the overburden of twin-tunnels. The maximum soil settlement is observed for the configuration with deep tunnel (H/D=6). In this case, the maximum soil settlement is induced between the two tunnels, it reaches about 22 mm. The increase in the overburden of tunnels causes an increase in the settlement in the central part of the twin-tunnels. It can be noted that in (H/D=1.5) the soil settlement at the central part of the tunnel is less than soil settlement above each tunnel, but in (H/D=3 and 6) the highest soil settlement happens in the central part of the twin-tunnels.

Figure 6c and 6d show the distribution of bending moment and thrust in the first tunnel. As expected, the increase in the overburden of tunnels results in an increase in the bending moment and thrust in the right tunnel.

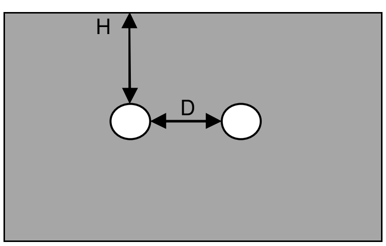

Figure 6a. Geometric configuration

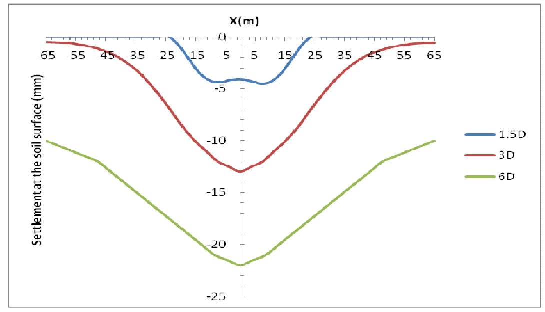

Figure 6b. Ground settlement

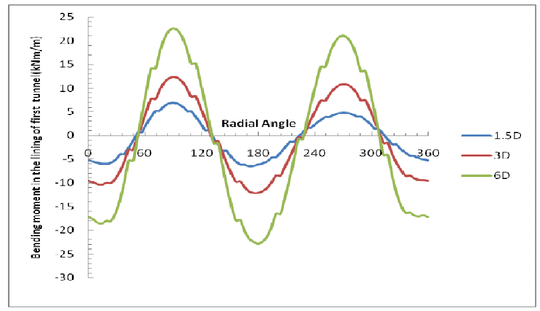

Figure 6c. Bending moment in the right tunnel

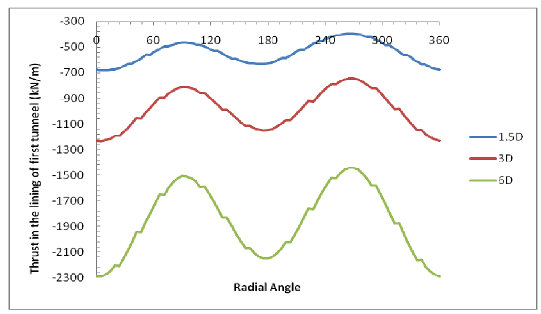

Figure 6d. Thrust in the right tunnel

Figure 6. Tunnels with horizontal alignment: influence of the staged construction and overburden of tunnels on the soil settlement and internal forces of first tunnel after construction of the second tunnel

3.4 Comparison between Simultaneous Construction and Staged Construction (Influence of the Construction Sequence and Overburden of Horizontal Tunnels)

Figure 7 presents the maximum settlement at the soil surface, maximum bending moment and thrust in the tunnels lining at the end of construction in simultaneous and sequence construction for three values of the over burden of twin tunnels H/D (1.5,3 and 6). Figure 7a shows, the maximum settlement at the soil surface is about 23 mm in H/D=6 in simultaneous construction. As shown in Figure 7b and c the maximum bending moment and thrust are about 22.5kNm/m and -2300kN/m in H/D=6 in right tunnel of staged construction. As expected, the increase in the overburden of tunnels causes an increase in the difference between simultaneous and staged construction.

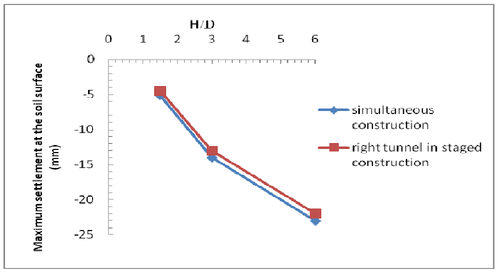

Figure 7a. Maximum ground settlement

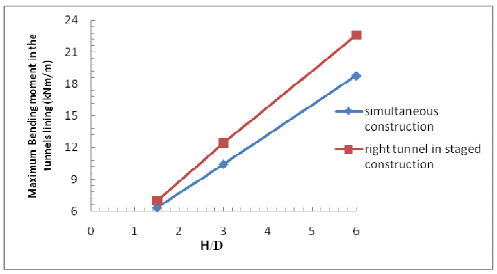

Figure 7b. Maximum bending moment in the tunnels lining

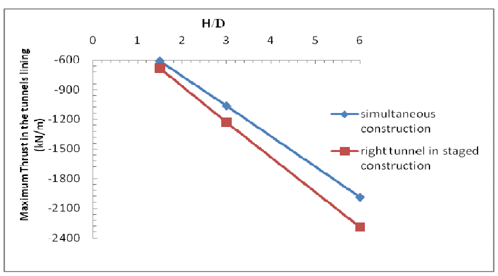

Figure 7c. Maximum thrust in the tunnels lining

Figure 7. Tunnels with horizontal alignment: comparison between simultaneous and staged construction, influence of the construction sequence and overburden of tunnels, on the soil settlement and internal forces, after construction of second tunnel

3.5 Effects of Pillar Width in Tunnels with Vertical Alignment in Staged Construction

Figure 8a shows the tunnel configuration considered in this section. The upper tunnel crown is located at 1.5D below the soil surface. Analysis was conducted for three values of the tunnel distance ratios S_y/D (1, 2 and 3). Two analyses were carried out. In the first one, the upper tunnel is constructed at first (reference case), while in the second analysis the lower tunnel is constructed at first (inverted case). Result of analysis shows that in both analyses, the internal forces in lower tunnel are higher than upper tunnel. Figure 8 shows, unlike the horizontal tunnels, the increase in the distance between tunnels or the increase in the overburden of bottom tunnels, induces an increase in the soil settlement, bending moment and thrust in the lower tunnel. It can be observed, the construction of upper tunnel at first, results to higher internal forces compared to that obtained by the construction of lower tunnel at first, but does not affect the soil settlement. In (S_y/D=1), the maximum bending moment in the reference case is about 24% higher than in the inverted case, while the thrust in the first case is higher by about 9% than that induced in the second case. In (S_y/D=2), the maximum bending moment in the reference case is about 16% higher than in the inverted case, while the thrust in the first case is higher by about 5% than that induced in the second case. In (S_y/D=3), the maximum bending moment in the reference case is about 8% higher than in the inverted case, while the thrust in the first case is higher by about 3% than that induced in the second case.

3.6 Comparison between Simultaneous Constructionn and Staged Construction

Figure 9 shows the maximum settlement at the soil surface, maximum bending moment and thrust in the tunnels lining at the end of construction, in simultaneous and staged construction, for four values of the tunnel distance ration S_y/D (0.5, 1, 2 and 3). (For better analyzing, the results of S_y/d=.5 are added to charts of this part). It can be observed that the lowest soil settlement happens in simultaneous construction and the results of reference case and inverted case of staged construction are very close. For example, in (S_y/D=2), the maximum soil settlement of simultaneous construction is about 10mm, but this value for reference case and inverted case of staged construction is about 11mm. The lowest internal forces happen in inverted case of staged construction and the results of simultaneous construction and reference case of staged construction are very close. For example, In (S_y/D=2), the maximum bending moment and thrust of inverted case are about 1050 kN/m and 9.5 kNm/m, but these for simultaneous construction and reference case of staged construction are about 1150 kN/m and 11.5 KNm/m. The increase in the distance between vertical tunnels (the increase in the overburden of bottom tunnels) induces a decrease in difference between simultaneous and staged construction, as for the horizontal tunnels.

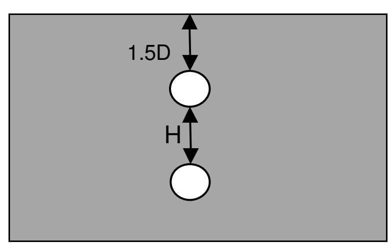

Figure 8a. Geometric configuration

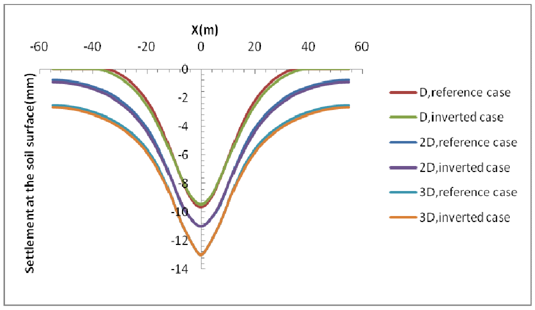

Figure 8b. Ground settlement

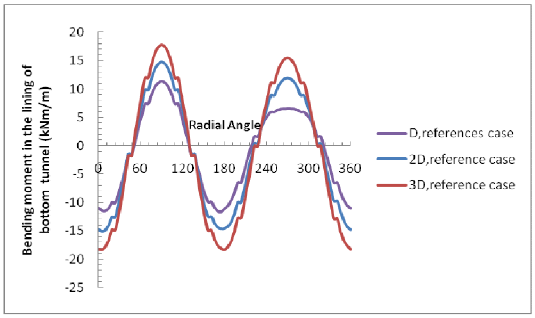

Figure 8c. Bending moment in the bottom tunnel, reference case

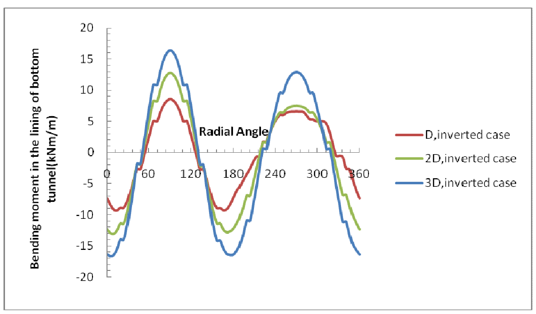

Figure 8d. Bending moment in the bottom tunnel, inverted case

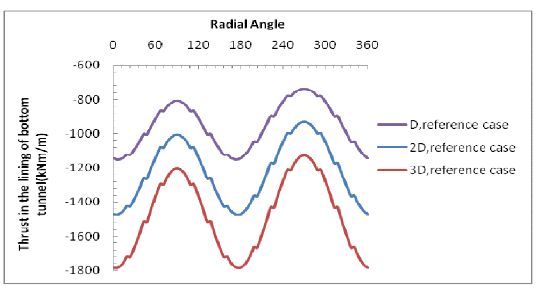

Figure 8e. Thrust in the bottom tunnel, reference case

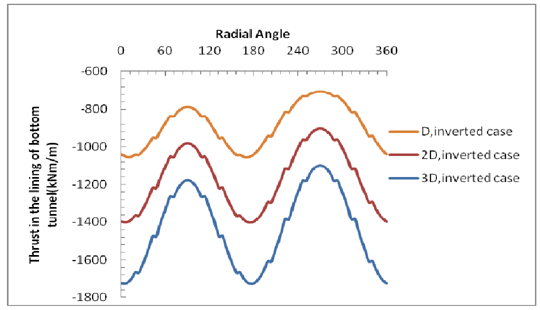

Figure 8f. Thrust in the bottom tunnel, inverted case

Figure 8. Tunnels with vertical alignment: influence of the staged construction and distance between tunnels, on the soil settlement and internal forces of bottom tunnel, after construction of second tunnel

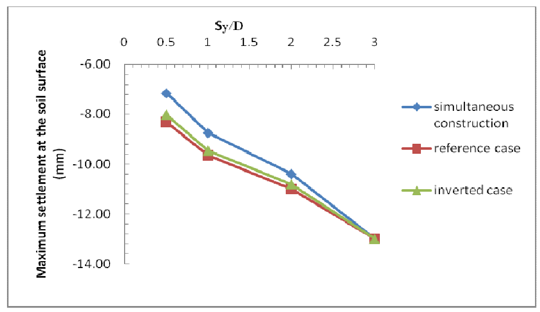

Figure 9a. Maximum soil settlement

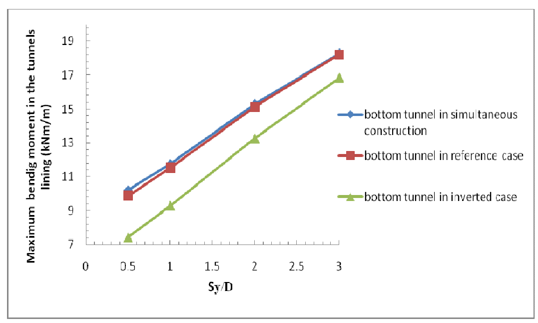

Figure 9b. Maximum bending moment in the tunnels lining

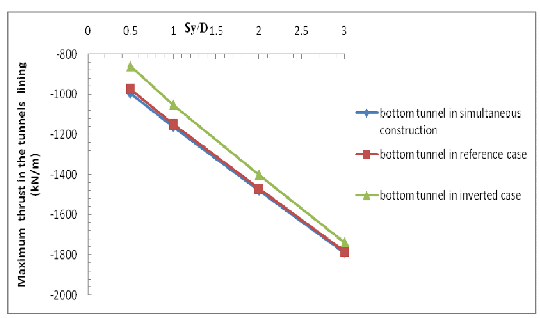

Figure 9c. Maximum thrust in the tunnels lining

Figure 9. Tunnels with vertical alignment: comparison between simultaneous and staged construction- influence of the construction sequence and distance between

tunnels on the maximum soil settlement and internal forces after construction of tunnels

3.7 Effects of Overburden in Tunnels with Vertical Alignment in Staged Construction

Figure 10a shows the tunnel configuration considered in this section. Analyses were conducted for three values of the overburden of upper tunnel H/D (1.5, 3 and 6). Tunnels vertical distance is considered D. Figure 10 shows the influence of the staged construction and overburden on the soil settlement, bending moment and thrust in the lower tunnel. It can be observed, the increase in the overburden of tunnels causes an increase in the soil settlement, bending moment and thrust in the lower tunnel, as for the horizontal tunnels. The maximum soil settlement is observed for the configuration with deep tunnel (H/D=6). Figure 10 shows the construction of upper tunnel at first leads to higher internal forces compared to that obtained by the construction of the lower tunnel at first, but does not affect the soil settlement. In (H/D=1.5), the maximum bending moment in the reference case is about 24% higher than in the inverted case, while the thrust in the first case is higher by about 7% than that induced in the second case. In (H/D=3), the maximum bending moment in the reference case is about 25% higher than in the inverted case, while the thrust in the first case is higher by about 8% than that induced in the second case. In (H/D=6), the maximum bending moment in the reference case is about 27% higher than in the inverted case. while the thrust in the first case is 9% higher by about 9% than that produced in the second case.

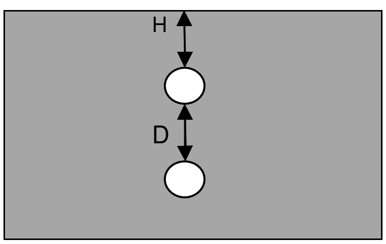

Figure 10a. Geometric configuration

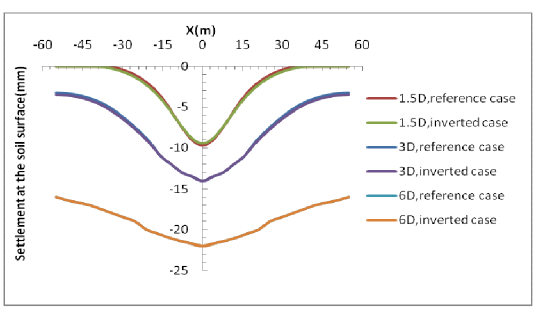

Figure 10b. Ground settlement

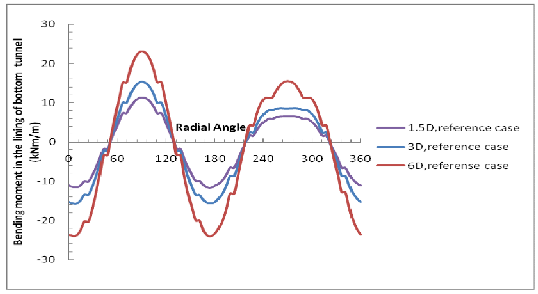

Figure 10c. Bending moment in the bottom tunnel, reference case

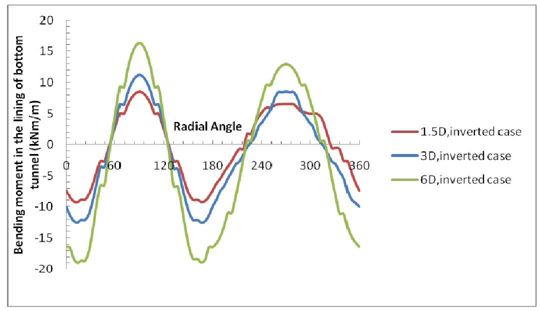

Figure 10d. Bending moment in the bottom tunnel, inverted case

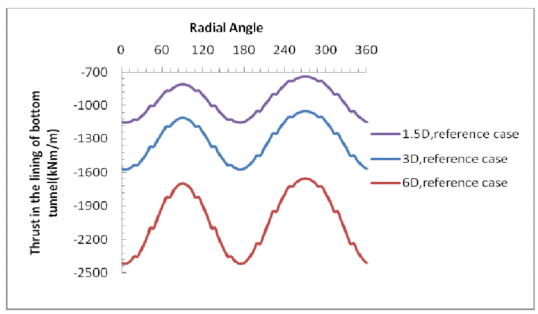

Figure 10e. Thrust in the bottom tunnel, reference case

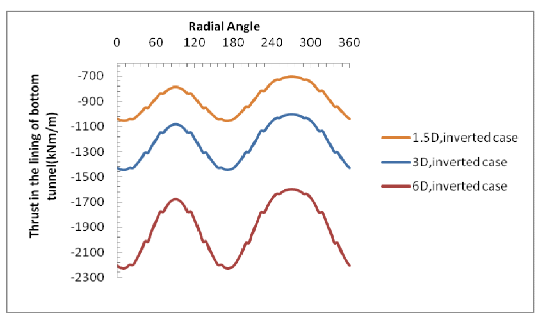

Figure 10f. Thrust in the bottom tunnel, inverted case

Figure 10. Tunnels with vertical alignment: influence of the staged construction and overburden of tunnels, on the soil settlement and internal forces of bottom tunnel, after construction of second tunnel

3.8 Comparison between Simultaneous Constructionn and Staged Construction (Influence of the

Construction Sequence and Overburden of Vertical Tunnels)

Figure 11 shows the maximum settlement at the soil surface, maximum bending moment and thrust in the tunnels lining at the end of construction in simultaneous construction and staged construction, for three values of the overburden of twin tunnels H/D (1.5, 3 and 6). It can be observed that the lowest soil settlement happens in simultaneous construction and the results of reference case and inverted case of staged construction are very close. The increase in the overburden of vertical tunnels causes an increase in difference between simultaneous and staged construction as for the horizontal tunnels. As shown, the lowest internal forces happen in inverted case of staged construction and the results of simultaneous construction and reference case of staged construction are very close.

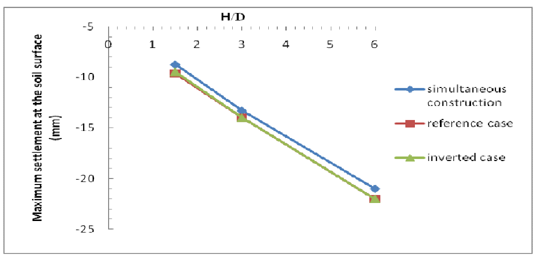

Figure 11a. Maximum ground settlement

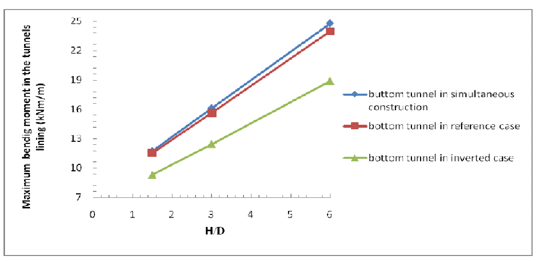

Figure 11b. Maximum bending moment in the tunnels lining

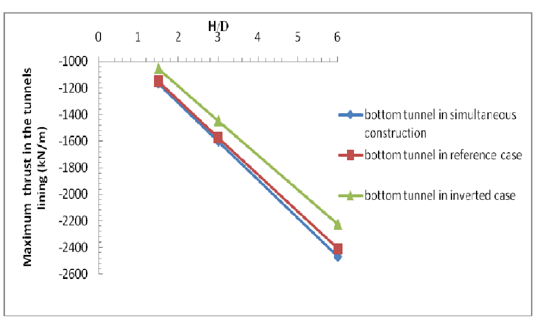

Figure 11c. Maximum thrust in the tunnels lining

Figure 11. Tunnels with vertical alignment: comparison between simultaneous and staged construction, influence of the construction sequence and depth of tunnels, on the maximum soil settlement and internal forces, after construction of tunnels.

4 CONCLUSIONS

This paper presents numerical models of relative position, construction sequence and overburden of twin tunnels and analyses conducted for two configurations of twin-tunnels: horizontally-aligned and vertically-aligned**.** The comparative study shows that the construction sequence, affects the soil settlement and internal forces. In horizontal tunnels, staged construction leads to lower settlement and higher internal forces than simultaneous construction. The increase in the distance between twin-tunnels results in a decrease in difference between simultaneous and staged construction, but the increase in the depth of twin-tunnels results in an increase in the difference between simultaneous and staged construction. In vertical alignment, the construction of upper tunnel at first, leads to higher internal forces compared to that obtained by the construction of the lower tunnel at first, but does not affect the soil settlement. In vertical alignment, the lowest soil settlement takes place in the simultaneous construction and the results of reference case and inverted case of staged construction are very close. In this case, the lowest internal forces occur in the inverted case and the results of simultaneous construction and reference case of staged construction are very close. The increase in the distance between vertical tunnels results in a decrease in the difference between simultaneous and staged construction and the increase in the overburden of tunnels causes an increase in the difference between the simultaneous and staged construction as for the horizontal tunnels.

In horizontal tunnels, increasing the tunnel pillar width, leads to lower soil settlement and internal forces, but increasing the overburden of tunnels results in higher soil settlement and internal forces. In vertical tunnels, increasing the tunnel distance or increasing the overburden of tunnels, leads to higher soil settlement and internal forces. For identical depth, the highest soil settlement and internal forces are obtained for the reference case of the vertically-aligned tunnels, while horizontally-aligned tunnels have the lowest soil settlement and internal forces.

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