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Research Article

Ground Settlements due to Construction of Triplet Tunnels with Different Construction Arrangements

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Combining two or three shield tunnels that are drilled consecutively at small intermediate distances into a single open cross section creates a larger useful tunnel area, while keeping the total construction area rather compact. However, the combination of several bored tunnel tubes into a singular cross section results in a complicated construction procedure. Current methodologies address the evaluation of the settlement trough for one single tunnel or two parallel tunnels only. This study aims at expanding the current methodologies to the multiple-tunnel geometry. Various construction orders and intermediate distances between the tunnels are evaluated using finite element analyses. The grout pressure method is applied in combination with the hardening strain with the small strain stiffness (HS small) constitutive model to investigate the relative magnitude of the settlements due to shield tunneling. It is concluded that the configuration with a Top-Left-Right construction sequence is the optimal arrangement. It results in 22.4% and 36.9% lesser settlements when compared to the equivalent horizontal twin tunnels spaced at 3*D* and the Left-Right-Top sequence, respectively.

1. Introduction

Due to higher traffic demands in urban areas, multiple tunnels are constructed closer to each other in various configurations, of which the horizontal twin tunnel is the most commonly adopted. Nowadays, triplet configurations are being planned as well with two tunnels lying horizontally adjacent and one lying vertically or skewed above them. This configuration results in excessive ground settlements that might cause damage to the nearby surface and subsurface structures. The factors contributing to these ground settlements include intermediate distance between the tunnels, their diameter, construction order, etc.

Ground movements and corresponding settlements resulting from a single tunnel and twin tunnels have been subjected to extensive investigations. Aforementioned parameters have been studied in detail using field measurements [1–6], laboratory testing of models [7–11], and numerical modelling [12–16]. Peck [5] performed detailed field analysis of tunnels and proposed a method for determining settlements caused by the tunnel construction which was later modified in order to determine cumulative settlements resulting from twin tunnels. Herzog [17] performed extensive testing on tunnels and proposed an equation to determine the maximum surface settlement resulting from the tunnel construction. Chapman et al. [18]

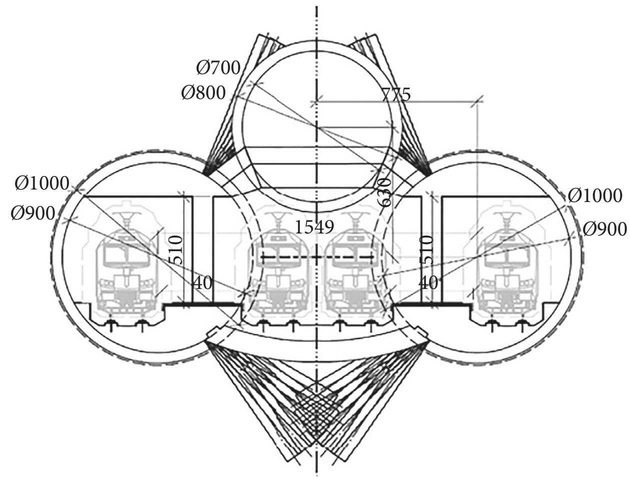


Figure 1: Proposed triplet configuration (dimensions in cm) (Schotte et al. [24]).

worked out settlement types and categorized the settlements caused by tunnels into five different types: due to stress relief during excavation, radial ones due to passage of tunnel boring machine (TBM), tail void settlements caused when soil fills the tail gap, settlements when the ground starts taking loads, and the time-dependent consolidation settlements. Mair [9] conducted centrifuge testing on tunnel models in clays to determine the surface settlements. Extensive studies have been carried out on twin tunnels as well. Addenbrooke and Potts [19] performed finite element modelling (FEM) on parallel lying tunnels in stiff clays. Consolidation effects were also considered, and their research culminated in the interaction between tunnels, an important factor contributing to the ground settlements. However, the interaction between tunnels becomes negligible when the intermediate spacing is greater than 7 times the diameter. Previous studies [2, 20] investigated different shapes of settlement troughs associated with twin tunnels and resulted in a modified method for evaluating settlements. Hunt [21] investigated the influence of new tunnel construction in the proximity of already created tunnels in order to study the effect of green field and brown field construction on the settlements. Chakeri et al. [22] found out that if the separation ratio between two tunnels exceeds 3 times the diameter, the settlement is no more dependent upon the interaction of the twin tunnels. Chapman et al. [23] also conducted similar research and concluded that greater the intermediate distance between two closely spaced tunnels, the lesser would be the settlement trough dependent upon their interaction. Qiu et al. [10] performed centrifuge tests on twin tunnels to study the induced ground settlements in loess strata. In summary, the literature study explains the behavior of single and twin tunnels and their interaction but very little or no knowledge is available regarding the interaction of triplets, their arrangement order, resulting settlements, etc., and thus, it requires further research as well.

This study comprises of detailed FEM analysis of proposed triplet tunnels, to be constructed under Brussels to accommodate the large amount of traffic. In this study, different geometric arrangements, various construction orders, and intermediate distances between the tunnels have been evaluated and discussed using PLAXIS 2*D*. Finally, settlement troughs are developed using the superposition technique, and the optimal construction sequence has been identified based upon the obtained settlement troughs.

2. Project Description

The city of Brussels, being the capital, suffers the largest mobility issues in Belgium. To tackle these issues, a new tunnel connection, aimed at strengthening the congested north-south railway link in the city, is currently under investigation. The project includes the construction of several kilometers of new railway lines, including new underground stations. In order to minimize the amount of disruption to the daily city life, the majority of the rail expansion will be tunneled.

Within the scope of the concept design of this new tunnel connection, a novel tunnel layout combining three independent shield-driven tunnels accommodating four railway tracks as shown in Figure 1 is considered as a valid alternative for traditional tunneling methods for the part between the main north and central stations.

Instead of creating two or three independent tunnels to accommodate the multiple railway tracks and safety evacuation areas, the tunnels are merged into a single entity. By combining several shield tunnels, drilled consecutively at a very small intermediate distance, into a single open cross section, a larger useful tunnel area can be created, while keeping the total construction area rather compact. In a highly urbanized area, where the sustainable use of the available space below the ground surface is nearly as important as the above ground level, this can be a key benefit [24].

However, the combination of several bored tunnel tubes into a singular cross section results in a delicate construction procedure. Apart from technical difficulties in merging the independent tubes, a main point of attention for tunneling in

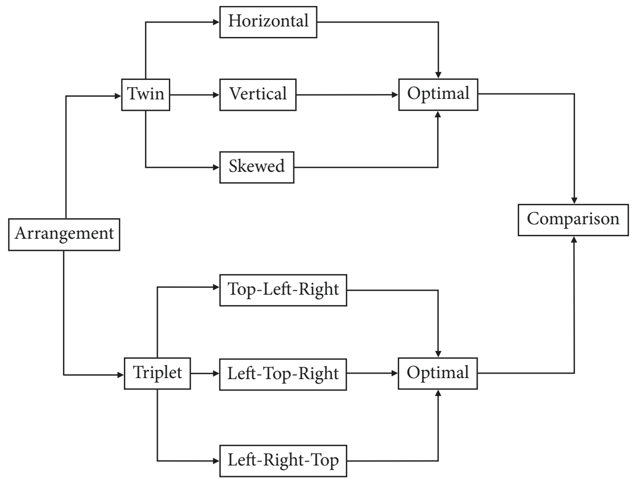


Figure 2: Flow chart showing the sequence of tunnels modelled.

the urban environment is the settlements that are dependent on the construction sequence and intermediate distance of these triplets. In the literature, solutions are mostly limited to calculation of the settlement trough for one single tunnel and twin tunnels.

3. Methodology

Triple tunnel configuration is modelled in PLAXIS 2*D* which is commonly used for geotechnical analysis as it provides a wide range of soil constitutive models that include soft soil, linear elastic (LE), Mohr–Coulomb (MC), hardening strain (HS) cam-clay, modified cam-clay, and elastoplastic. Additionally, PLAXIS 2*D* is capable of incorporating the nonlinear interplay between the tunnel and surrounding soils, the elastoplastic behavior and the complexity of the construction operations as well. To determine the optimal sequence of the triplets, the constitutive model that approximates the field measurements well is selected on the basis of already available literature and the second Heinenoord tunnel data. Then, the optimal intermediate distance between twin tunnels lying in different combinations is modelled. After selecting the appropriate sequence for twin tunnel construction, the third tunnel is modelled along with the already selected twin sequence. Finally, the conclusions are drawn based on the obtained settlement troughs. The details about the sequences modelled in this study are provided in the flow chart given in Figure 2.

4. Modelling and Ground Settlement Curves

4.1. Selection of the Constitutive Model. Dias and Bezuijen [25] performed a detailed analysis of a single tunnel of 8 m diameter and 30 m below the ground surface, as shown in Figure 3(a). In this study, LE, MC, Mohr–Coulomb with dilatancy factor (MC.D), HS, and hardening strain with small strain stiffness (HS small) models are compared. Based on this research, it is concluded that the MC model overestimates the settlements while the HS small model is the most appropriate model as it gives the most realistic settlement results. Möller and Vermeer [26] compared the field data of a 16 m deep and 8.3 m diameter tunnel with HS and HS small models and concluded that the HS small model gives settlements within 20% from the field settlements, as shown in Figure 3(b).

For the structural modelling, the grout pressure method is more realistic when compared to the contraction method and the stress reduction method as it models the construction method itself, results in accurate width of settlement troughs, and yields the structural forces as well along with the displacements [26, 27]. Hence, the triplet configuration is modelled using the HS small model in conjunction with the grout pressure method.

For this study, a self-composed grout pressure method is proposed, which consists of six "construction phases." The proposed model is capable of simulating all construction stages that belong to a slurry tunnel boring machine (TBM) excavation process [24]. Table 1 provides an overview of the utilized construction phases and their characteristics. The face pressures [28, 29] and tail void pressures [30–32] were carefully determined based on existing research.

4.2. Comparison between 2D and 3D Modelling. 3*D* analyses are commonly employed to model large complex tunneling projects, and they require large model size and high computational efforts. Therefore, 2*D* alternatives are used to enhance the computational efficiency, and most of the researchers are now focusing on 2*D* modelling. Möller [33] performed detailed 2*D* and 3*D* HS small models analysis to obtain the settlement trough for the second Heinenoord tunnel. It was concluded that both resulted in the same transverse surface settlement troughs and noted that 2*D* modelling performs well if reasonable face pressures and tail void pressures are applied.

4.3. Mesh Dimensions and Boundary Conditions. Meißner [34] recommends to provide a distance of 4 to 5 times the

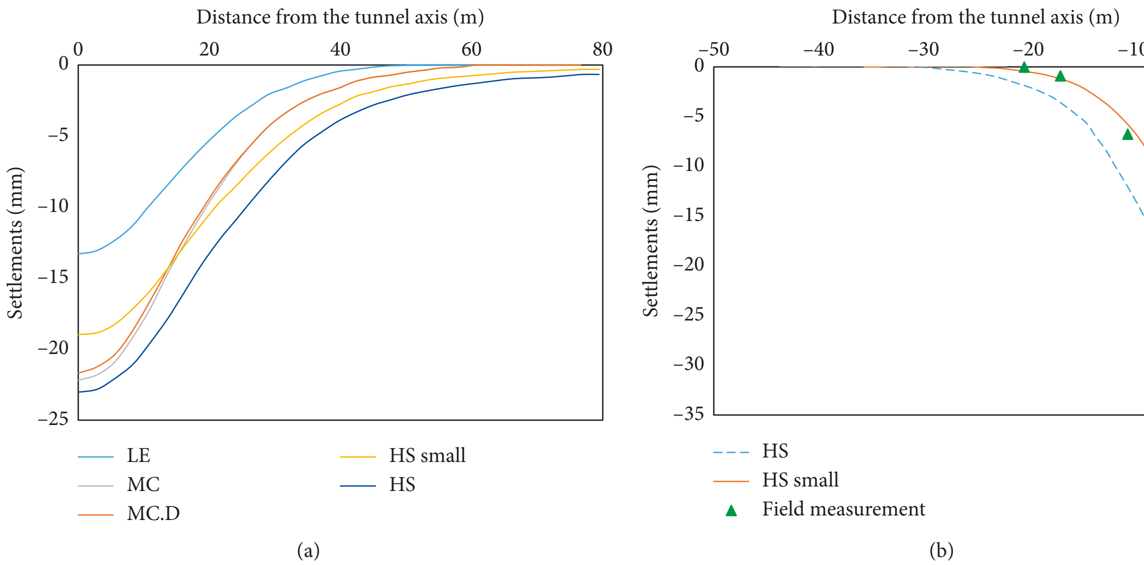


Figure 3: (a, b) Comparison of settlements obtained from constitutive models (Diaz and Bezuijen [25]) and field measurement (Möller and Vermeer [26]).

Table 1: PLAXIS 2D construction phases (Schotte et al. [24]).

No.	Phase	Action	Applied pressure (MPa)	Pressure increment (MPa/m)
0	Initial	—	—	—
1	Face pressure, σ_f	(i) Deactivate soil cluster (ii) Apply face pressure	$\sigma_f = \sigma_a + u + 0.02$	0.012
2	TBM	(i) Remove face pressure (ii) Apply TBM	—	—
3	Tail pressure 0, σ_{t0}	(i) Remove TBM (ii) Apply tail pressure 0	$\sigma_{t0} = \sigma_f + 0.1$	0.016
4	Tail pressure 1, σ_{t1}	(i) Apply tail pressure 1	$\sigma_{t1} = \sigma_{t0} - 0.03$	0.011
5	Tail pressure 2, σ_{t2}	(i) Apply tail pressure 2	$\sigma_{t2} = u + 0.03$	0.011
6	Final state	(i) Remove tail pressure 2 (ii) Activate tunnel lining	—	—

U, pore water pressure; σ_a, active earth pressure.

Table 2: Overview of the soil parameters of the Heinenoord tunnel.

Parameters	Soil layers		
	Fill	Clayey sand	Sand
Saturated soil density, γ_{sat} (kN/m^3)	17.2	20	20
Effective cohesion, c' (MPa)	$3 * 10^{-3}$	$7 * 10^{-3}$	10^{-5}
Effective angle of friction, $Ø'$ (degrees)	27	31	35
Poisson ratio, v	0.2	0.2	0.2
Initial shear modulus, G_0^{ref} (MPa)	52	88	175
Shear strain level at which the secant shear modulus (G_s) is reduced to 72.2%, $\gamma_{0.7}$	$5 * 10^{-4}$	$5 * 10^{-4}$	$5 * 10^{-4}$
Power indicating the stress-level dependency of the stiffness, m	0.5	0.5	0.5
Tangent stiffness modulus, E_{oed}^{ref} (MPa)	14	7	35
Unloading-reloading stiffness modulus, E_{ur}^{ref} (MPa)	42	35	105

tunnel diameter from the tunnel center to the vertical mesh boundaries and a distance of 2 to 3 times the tunnel diameter from the tunnel center to the bottom mesh boundary. Möller [33] suggested the following equation for calculating the mesh dimensions:

$$w = 2D\left(1 + \frac{H}{D}\right), \quad (1)$$

where w is the width of the mesh, D is the diameter of the tunnel, and H is the height from the ground surface to the

Table 3: Overview of the soil parameters used for tunnel sequences (Schotte et al. [24]).

Soil parameters	
Soil gradation	
Sand (%)	77
Silt (%)	07
Clay (%)	16
Bulk density, γ_b (kN/m^3)	17
Saturated soil density, γ_{sat} (kN/m^3)	19.8
Tangent stiffness modulus, E_{oed}^{ref} (MPa)	3
Effective cohesion, c' (MPa)	$2 * 10^{-3}$
Effective angle of friction, $Ø'$ (degrees)	34.3
Effective angle of dilatancy, ψ' (degrees)	4.3
Poisson ratio, v	0.3
Active earth pressure coefficient, K_a	0.28
Initial shear modulus, G_0^{ref} (MPa)	94
Relative density, D_r (%)	50
Unloading-reloading stiffness modulus, E_{ur}^{ref} (MPa)	90
Power indicating the stress-level dependency of the stiffness, m	0.544
Shear strain level at which the secant shear modulus (G_s) is reduced to 72.2%, $\gamma_{0.7}$	$1.5 * 10^{-4}$
Failure ratio, R_f	0.938

tunnel crown. The mesh dimensions for each sequence are calculated using both methods, and the larger dimensions are opted for modelling to avoid distortions and errors. 15-noded triangular elements are selected while the size of each element is kept equal to 0.25 m to ensure more accurate settlement results. The boundary conditions are selected as viscous for the lateral boundaries, while the top boundary is taken as free as has been proposed in the literature to accurately capture the deformation phenomena.

4.4. Model Validation. The constitutive, structural model, and mesh element sizes selected in this study are also validated for accuracy by comparing it with the field measurements of the second Heinenoord tunnel given by Möller [33]. The detailed soil parameters and layers used in this validation are presented in Table 2 while lining parameters are enlisted in Table 3. Comparison of software modelling with field data and detailed displacement contours can be seen in Figures 4(a) and 4(b). From the figures, it is clear that the results of the FEM analysis are in close agreement with the data obtained from the field with a minute difference of just 1.4 mm. Therefore, same models and mesh element sizes are used for the entire study.

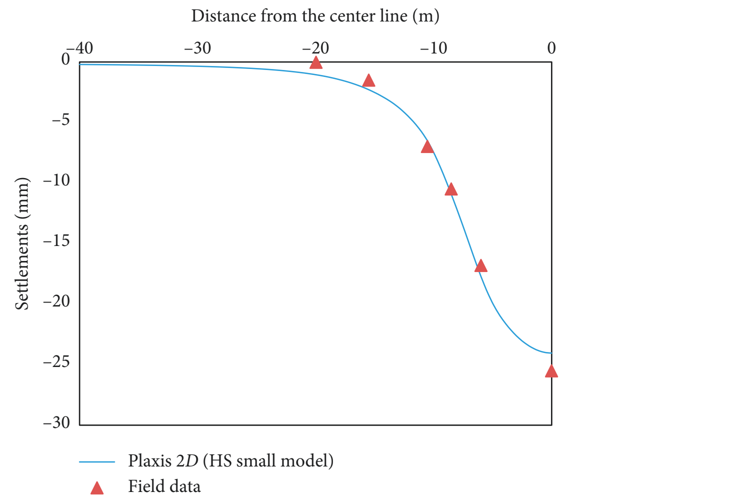
4.5. Soil and Lining Properties. The soil profile used in this study comprises of a thick sand layer with a groundwater table (GWT) at 5 m below the ground surface. The soil is classified as clayey sand (SC) according to Unified Soil Classification System (USCS). The soil parameters are enlisted in Table 4.

The tunnel lining is 0.5 m thick for both the 8 m and 10 m diameter tunnels. The stiffness and other parameters are calculated based on these thicknesses. The weight of the lining is calculated per meter tunnel lining in plane of the tunnel's cross section and per meter in the longitudinal direction of the tunnel axis. A density of 260 kg/m³ [30] is assumed for the gantry in order to be able to calculate the weight of the TBM. The TBM is assumed to be undeformable [24]. The material characteristics of the tunnel linings are listed in Table 4.

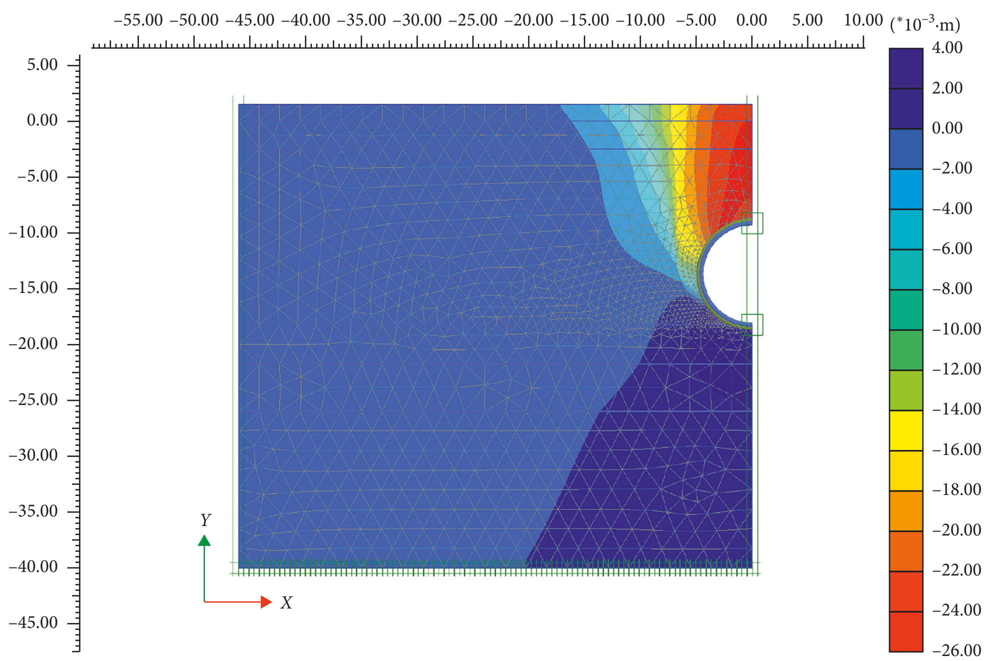
5. Results and Discussion

5.1. Twin Tunnel Configuration. To check for the proper arrangement of triplet tunnels, the twin tunnel configuration is modelled first. In this approach, twin tunnels are placed in three different arrangements, i.e., parallel (horizontally and vertically) and skewed with an angle of 39° as, shown in Figures 5(a), 6(a), and 7(a), respectively. The aforementioned angle between skewed tunnels is chosen in order to reflect the same inclination as in the triplet configuration. The settlements are analyzed for all the three arrangements, and the effect of intermediate distance between them is also taken into consideration.

Figures 5(b) and 5(c) show the surface settlement troughs and detailed displacement contours for the horizontal twin tunnels, respectively. From Figure 5(b), it is clear that the intermediate distance of 0.55D results in the maximum amount of settlement, and as the intermediate distance between two parallel lying horizontal tunnels increases, the settlements decrease. It is also observed that if the intermediate distance is further increased from 2D to 3D, the difference in settlements is just 2.5%. The reason is that at 0.55D, there is a large overlapping shear zone in between, which gets narrowed from minimal to none as the distance increases from 0.55D to 3D. Hence, it can be concluded that beyond 2D, there is a negligible effect of interaction between the twin tunnels.



(a)

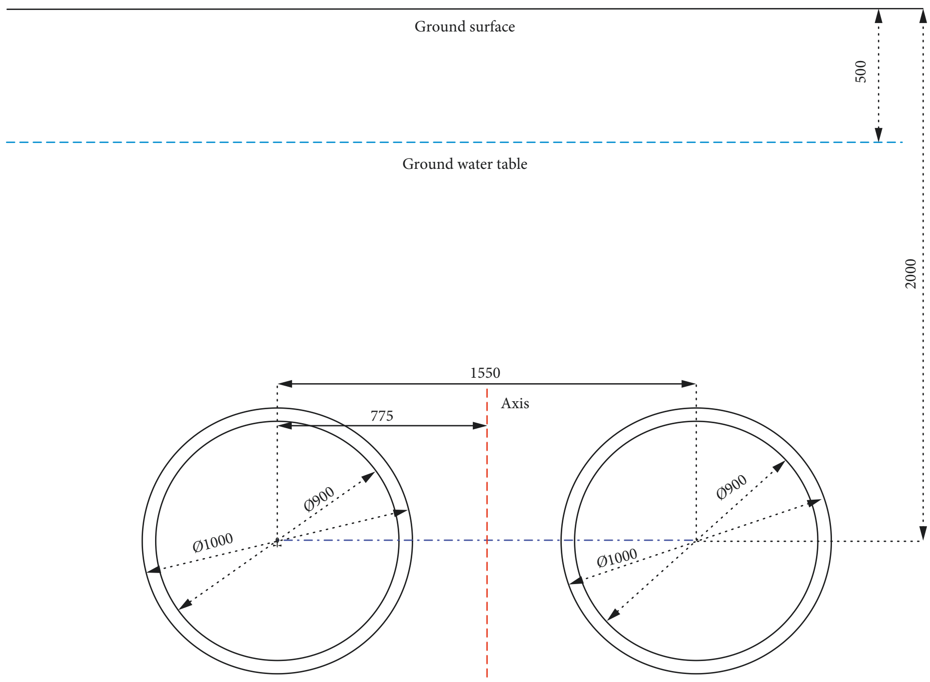


(b)

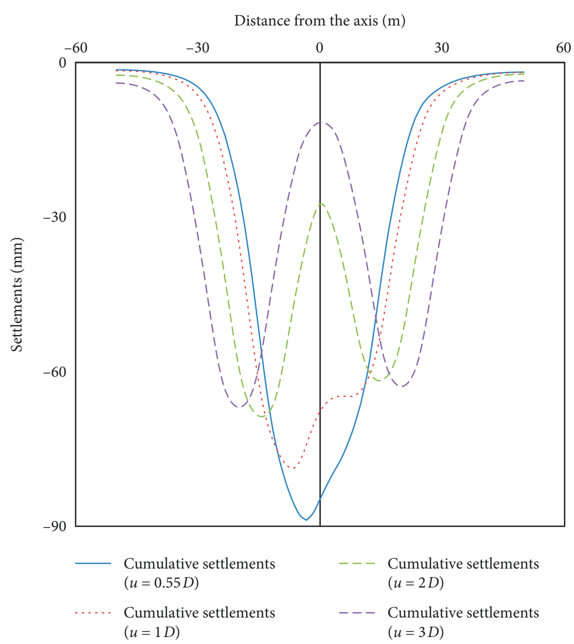
FIGURE 4: (a) Comparison of PLAXIS 2*D* results with field data of Heinenoord tunnel. (b) Detailed displacement contours of Heinenoord tunnel.

TABLE 4: Overview of the tunnel lining parameters (Schotte et al. [24]).

Parameter	Bottom tunnels	Top tunnel	Heinenoord tunnel
Tunnel diameter, D (m)	10	8	8.3
Young modulus of concrete, E_c (MPa)	37	37	37
Unit weight of concrete, γ_c (kN/m^3)	24	24	24
Lining thickness, t (m)	0.5	0.5	0.4
Lining surface area, A (m^2)	14.92	9.55	10.93
Moment of inertia, I (m^4)	168.8	69.1	84.05
Normal stiffness, EA (kN)	$1.85 * 10^7$	$1.48 * 10^7$	$1.05 * 10^4$
Flexural rigidity, EI (kNm^2)	$3.85 * 10^5$	$1.97 * 10^5$	$2.68 * 10^4$
Lining weight, W_{Lining} (kN/m)	12.02	9.61	24
TBM weight, W_{TBM} (kN/m)	18.1	14.5	14.5

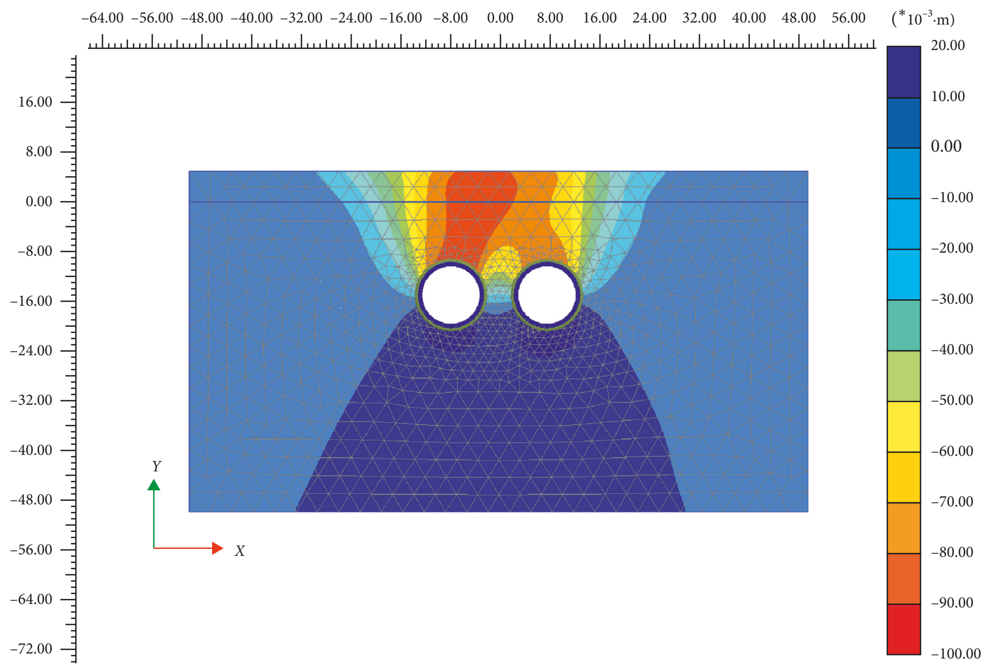


(a)



(b)

FIGURE 5: Continued.



(c)

FIGURE 5: (a) Twin tunnels ($u = 0.55D$) in horizontal configuration (dimensions in cm). (b) Settlement trough of horizontal twin tunnels. (c) Displacement contours of horizontal twin tunnels ($u = 0.55D$).

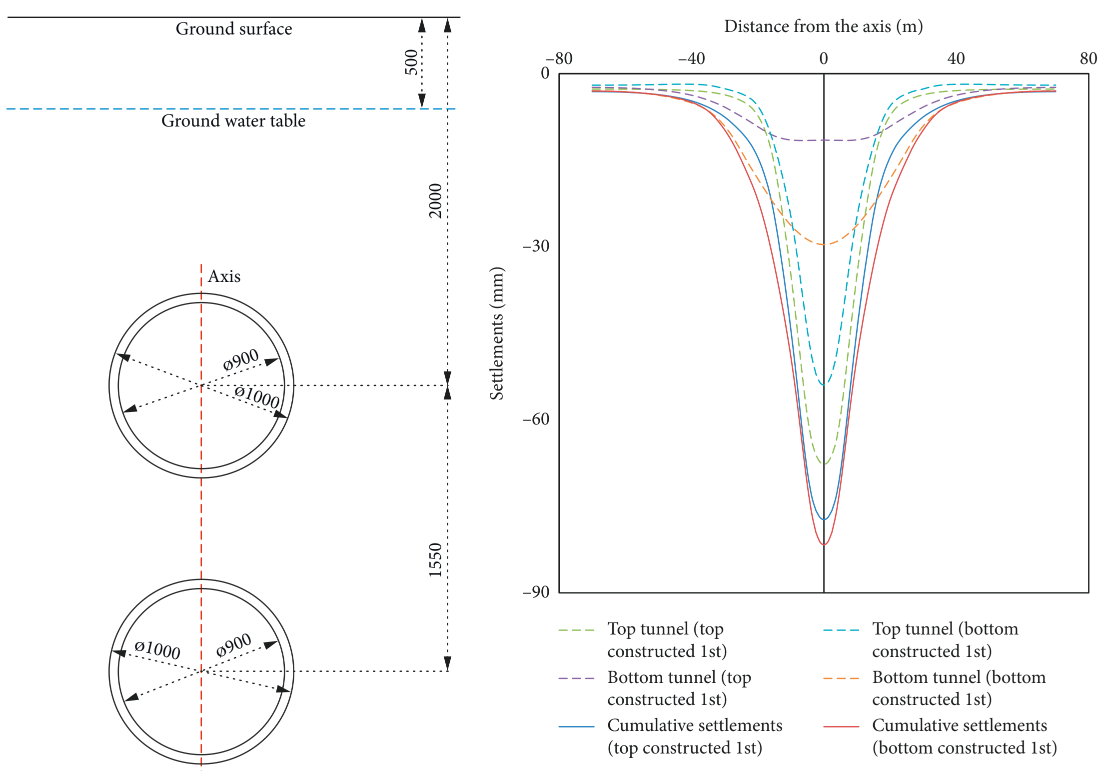
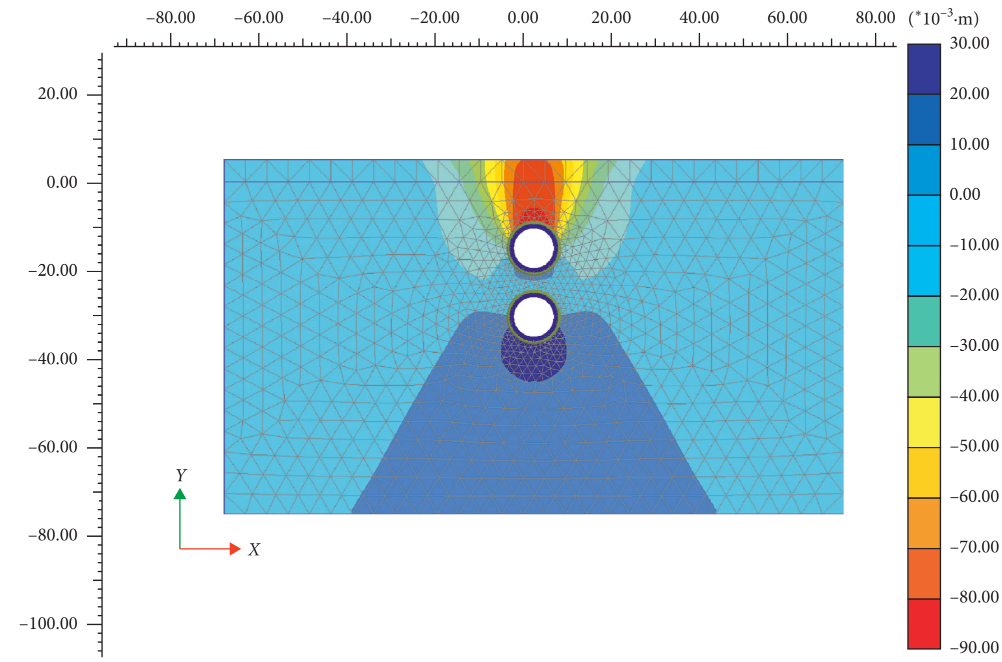


FIGURE 6: Continued.



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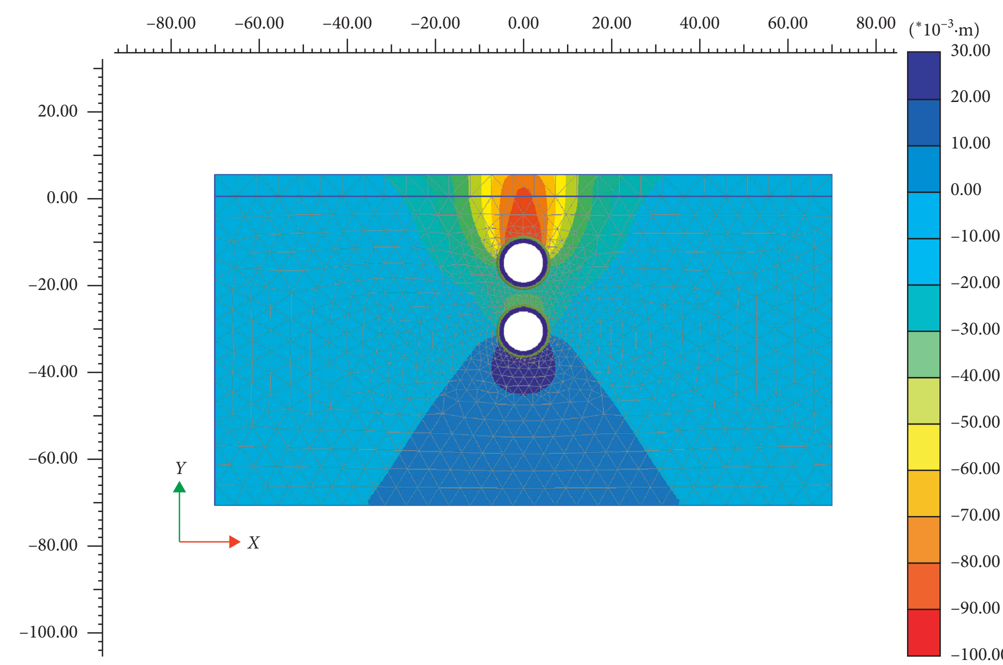


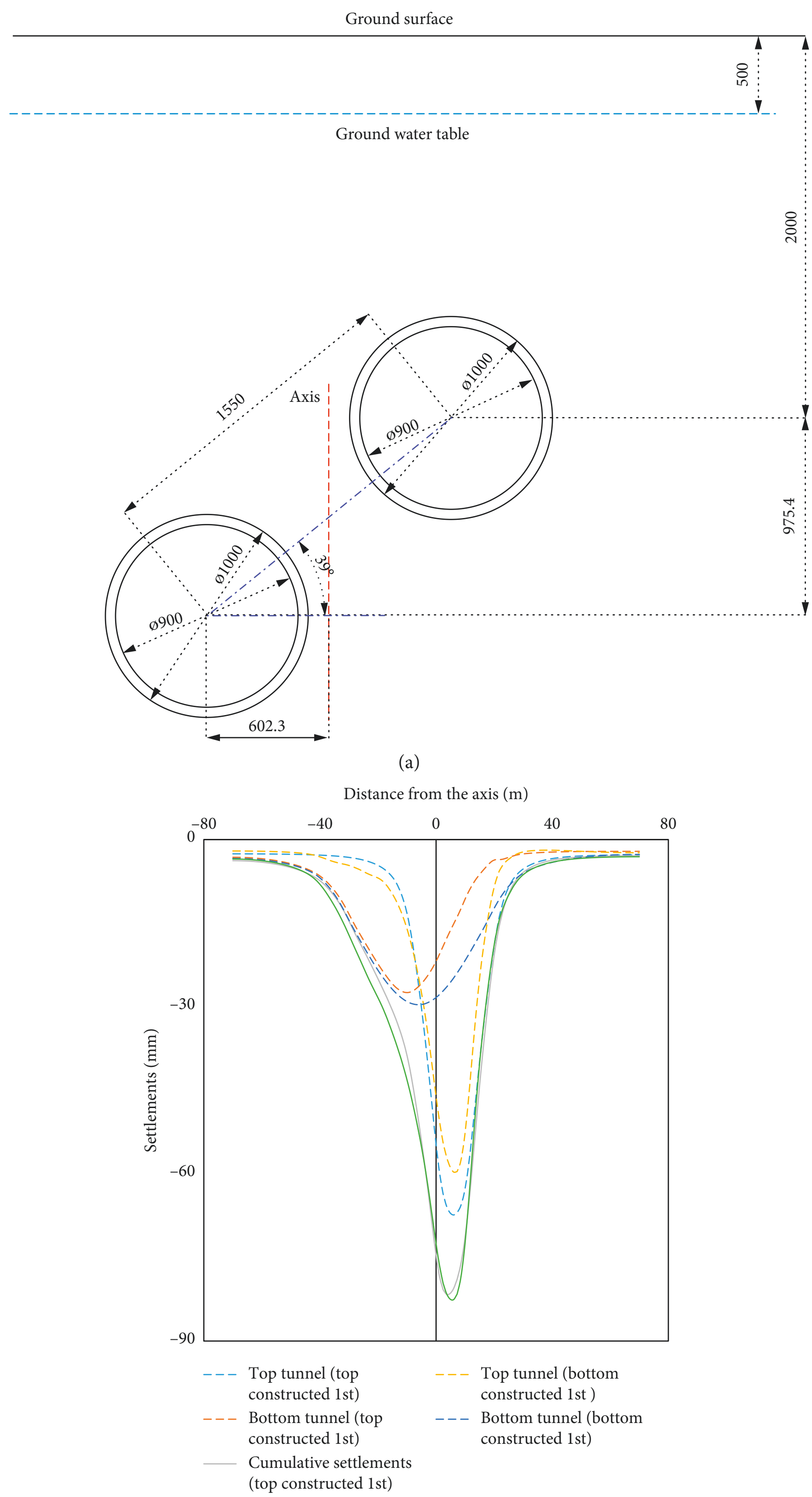
(d)

Figure 6: (a) Twin tunnels ($u = 0.55D$) in vertical configuration (dimensions in cm). (b) Settlement trough of vertical twin tunnels ($u = 0.55D$). (c) Displacement contours of vertical twin tunnels (top constructed first). (d) Displacement contours of vertical twin tunnels (bottom constructed first).

When the tunnels are placed in a vertical arrangement, it is observed from Figure 6(b) that the construction sequence plays an important role. If the top tunnel is constructed before the bottom one, settlements are reduced by 2.7%. The detailed displacement contours for each case are shown in Figures 6(c) and 6(d).

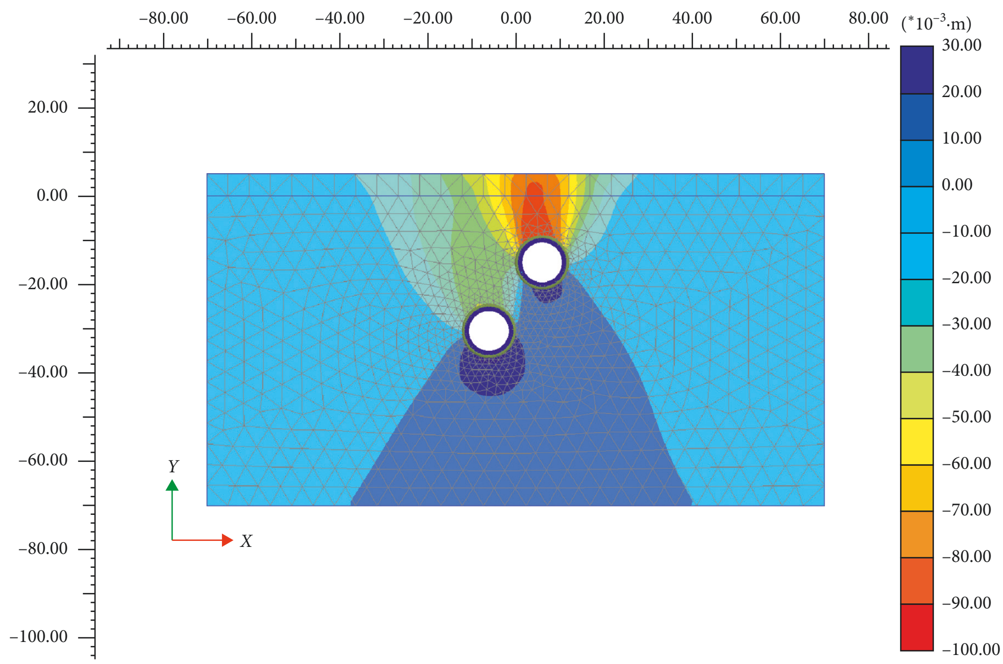
When tunnels are placed in the skewed arrangement with the tunnel axes making 39° with the horizontal, construction of the top tunnel first results in settlements being 1.25% smaller as compared to when the bottom tunnel is constructed first, as shown in Figure 7(b). The detailed displacement contours for each case are shown in Figures 7(c) and 7(d).

The comparison of the amount of settlements resulting from each of the arrangements at an intermediate distance (u) of $0.55D$ can be seen in Table 5. From the results, it is



(b)

Figure 7: Continued.



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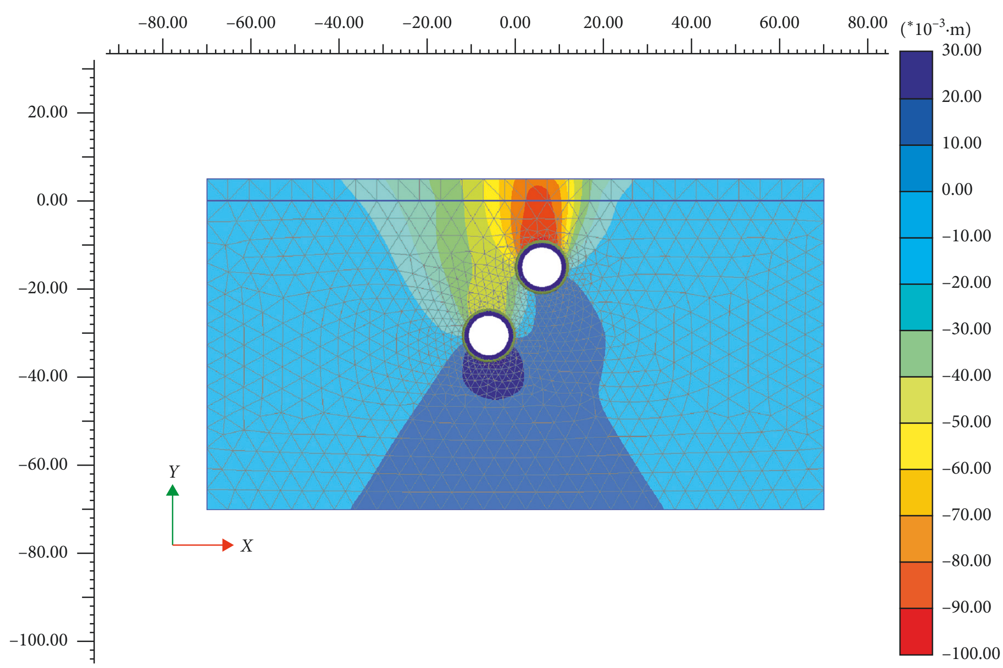


(d)

Figure 7: (a) Twin tunnels ($u = 0.55D$) in skewed configuration (dimensions in cm). (b) Settlement trough of skewed twin tunnels ($u = 0.55D$). (c) Displacement contours of skewed twin tunnels (top constructed first). (d) Displacement contours of skewed twin tunnels (bottom constructed first).

concluded that horizontal twins result in almost 8.5% larger settlements in comparison with the vertical and skewed arrangements, which produce more or less the same amount of settlements.

5.2. Triple Tunnel Configuration. After the optimal twin arrangement, the triangular configuration of the triplets as shown in Figure 8(a) is investigated to determine their optimal construction sequence.

In this approach, three different arrangements are modelled: the top tunnel constructed first, the top tunnel constructed second, and the top tunnel constructed last. The settlement contours and ground settlement curves for each of the arrangement are developed and also compared with the equivalent horizontal twin tunnels that can be provided

Table 5: Maximum settlements resulting from different twin arrangements.

Twin tunnels arrangement	Maximum settlement (mm)
Horizontal	−88.83
Vertical (top constructed first)	−77.03
Vertical (bottom constructed first)	−81.46
Skewed (top constructed first)	−81.27
Skewed (bottom constructed first)	−82.40

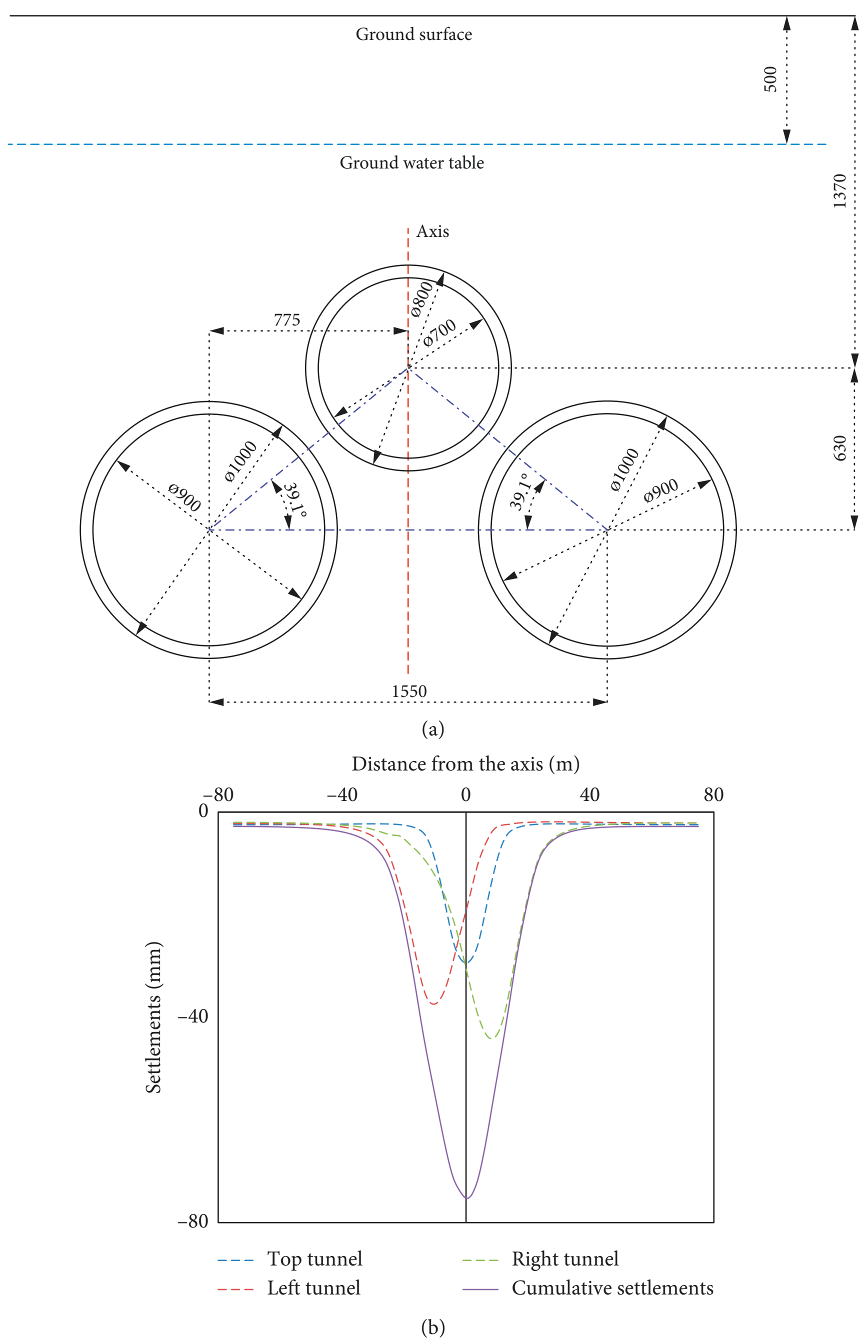
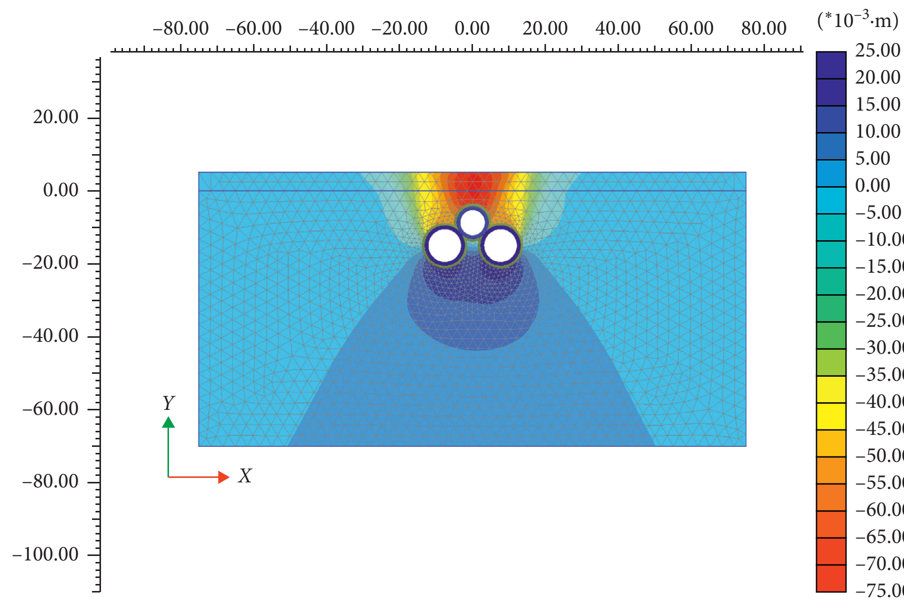


Figure 8: Continued.



(c)

Figure 8: (a) Triplet tunnel configuration (dimensions in cm). (b) Settlement trough of Top-Left-Right tunnel sequence. (c) Displacement contours resulting from Top-Left-Right sequence.

as an alternative to accommodate the same four railway tracks. The details are as follows.

5.2.1. Top-Left-Right Sequence. In this approach, the top tunnel is constructed first, followed by the construction of the left tunnel and right tunnel sequentially afterwards. Figure 8(b) shows the individual surface settlement troughs for each of the tunnels as well as the cumulative settlement trough, while Figure 8(c) shows the detailed displacement contours. From the settlement curves, it can be noticed that the maximum cumulative ground settlement resulting from the triplets is 75 mm.

5.2.2. Left-Top-Right Sequence. In this approach, the top tunnel is constructed right after the completion of the left bottom tunnel, followed by right tunnel construction in the end. Figure 9(a) shows the individual surface settlement troughs for each of the tunnels as well as the cumulative settlement trough, while Figure 9(b) shows the detailed displacement contours. From the settlement curves, it can be noticed that the maximum cumulative ground settlement resulting from the triplets is 98.75 mm, which is almost 32% larger than the settlement that results from the top tunnel construction first. The settlement trough of the top tunnel is also showing a ground heave of about 1.3 mm.

5.2.3. Left-Right-Top Sequence. In this approach, the bottom tunnels are constructed first, followed by the top tunnel in the end. Figure 10(a) shows the individual surface settlement troughs for each of the tunnels as well as the cumulative settlement trough, while Figure 10(b) shows the detailed displacement contours. From the settlement curves, it can be noticed that the maximum cumulative ground settlement resulting from the triplets is 107 mm, which is over 8% larger than the settlement resulting from the construction of the top tunnel second and 43% larger than when the top tunnel is constructed first. From Figure 10(a), it can also be noted that a ground heave of about 4.3 mm is occurring, which is a substantial amount and can cause problems for the structures and foundations in the proximity. The reason for this is that after the construction of bottom tunnels, due to grouting and hardening of the lining, surrounding soil has got consolidated and the construction of the top tunnel and its lining would produce a small amount of heave deformations on the ground surface which is less consolidated in comparison with the surroundings.

5.3. Equivalent Horizontal Twin Tunnels. If twin tunnels instead of triplets are provided to accommodate the same amount of four rail tracks, tunnels of bigger size will be required. Their diameter can be calculated using the following equation:

$$\text{diameter}\,(D) = 2R_w + 2X_{R/T} + 2L_t, \quad (2)$$

where R_w is the rail width, $X_{R/T}$ is the clear distance between the rail and tunnel, and L_t is the lining thickness.

Substituting R_w as 4.03 m, $X_{R/T}$ as 0.85 m, and L_t as 0.5 m as shown in Figure 1, the diameter (D) of each tunnel should

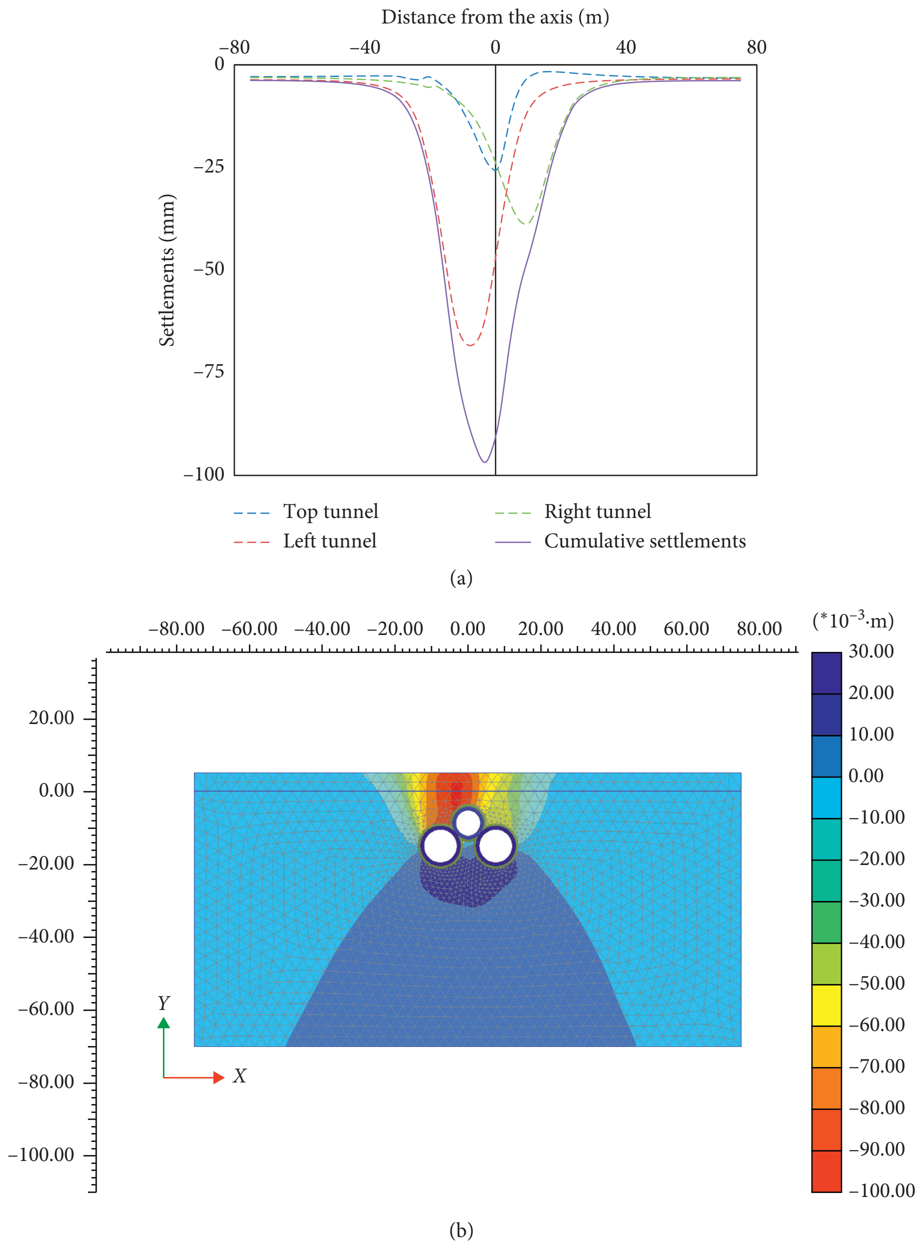
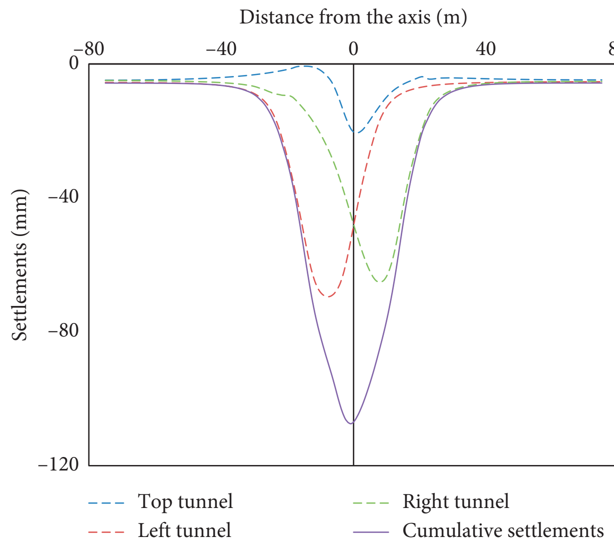


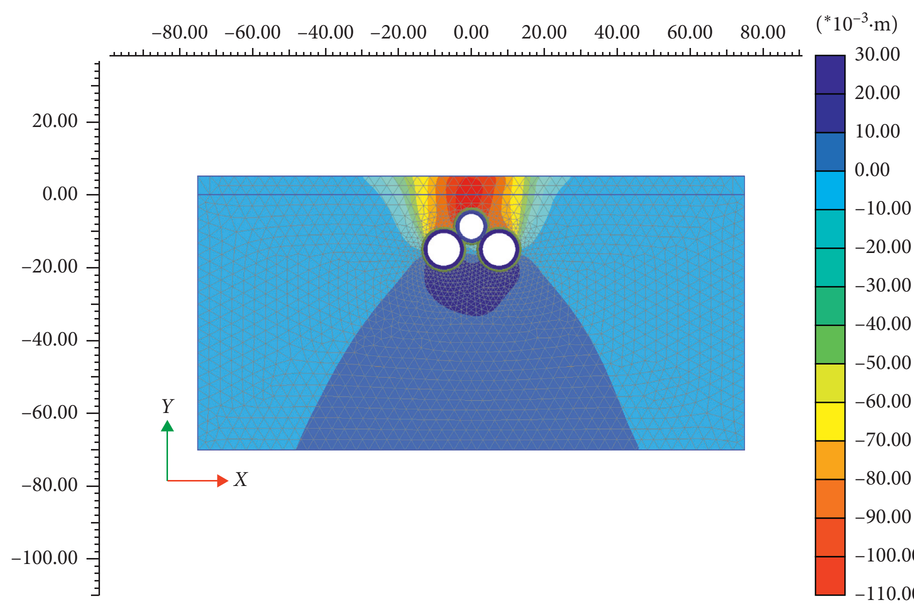
Figure 9: (a) Settlement trough of Left-Top-Right tunnel sequence. (b) Displacement contours resulting from Left-Top-Right sequence.

be approximately 11 m. The intermediate distance (u) is kept as $3D$ for the analysis. Figure 11(a) shows the individual settlement trough for each tunnel as well as the cumulative settlement trough, while Figure 11(b) shows the detailed displacement contours.

5.4. Comparison of Twin Horizontal Tunnels and the Triplet Configuration. The settlement troughs shown in Figure 12 clearly indicate that construction of the top tunnel at the end results in the largest amount of settlements, as well as the ground heaving. Left-Top-Right sequence produces negligible ground heaving and almost equal settlements as produced by equivalent horizontal twins. The Top-Left-Right sequence produces the least amount of settlements and almost no ground heaving. Equivalent horizontal twin tunnels (even if placed at an intermediate distance of $3D$) result in 18.3% larger settlements than the Top-Left-Right sequence and almost identical settlements as produced by the Left-Top-Right sequence. For smaller interdistances, which will often be preferred or required in actual situations, the equivalent twin tunnels will show even larger settlement differences compared to the triplet configuration, as indicated in Figure 5(b).



(a)



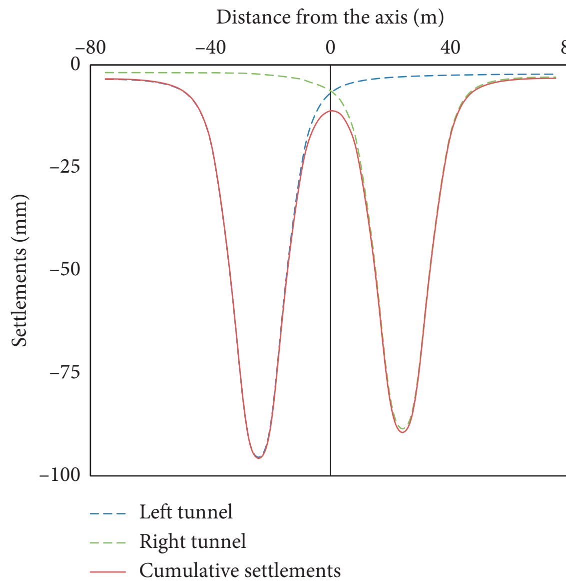
(b)

FIGURE 10: (a) Settlement trough of Left-Right-Top tunnel sequence. (b) Displacement contours resulting from Left-Right-Top sequence.

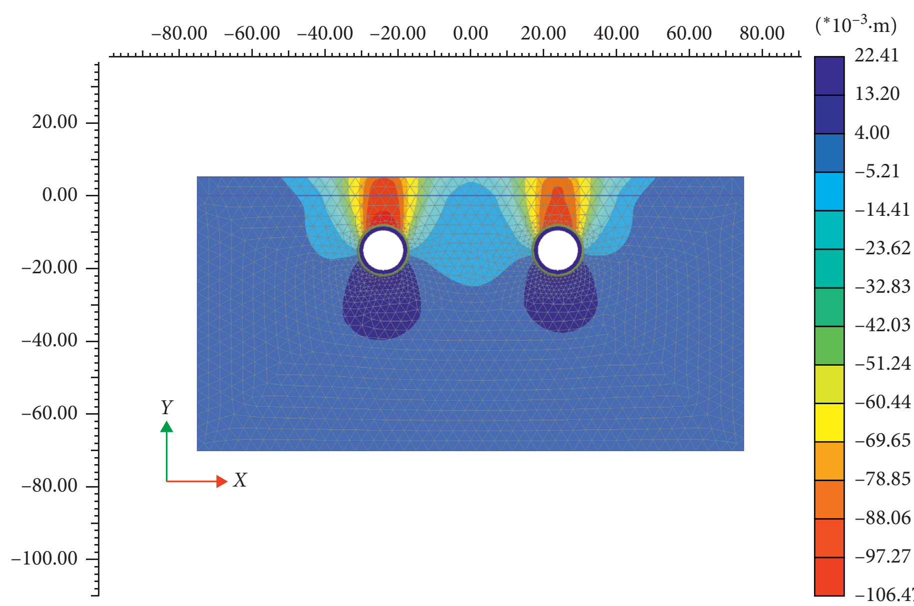
5.5. Discussion. This research has incorporated a novel tunnel construction approach in 2*D* and provides a detail insight into the deformation patterns that can occur depending on different tunnel arrangements and construction sequence. This study encompasses all possible stages during the tunnels construction that include the passage of TBM, face pressures, tail void grouts, and final lining in order to capture the deformations more accurately. The results obtained provide a very clear basis for comparison between different arrangements and all of the sequences. However, it is understood that 2*D* modelling can capture the lateral deformations only, which are although the most important but in order to have a better look at the longitudinal behavior of the tunnel too, it should be figured out in 3*D* modelling including the effect of uniform and nonuniform gap convergence between the shield and the ground as it was not covered by the scope of this research. This would further refine the obtained deformation troughs for different scenarios.

6. Conclusions

The main goal of this study was to investigate the optimal construction sequence for a triple tunnel configuration that results in the least amount of settlements while serving the desired demands of accommodating huge traffic. Following conclusions are drawn from this study:



(a)



(b)

FIGURE 11: (a) Settlement trough equivalent horizontal twin tunnels ($u = 3D$). (b) Displacement contours resulting from equivalent horizontal twin tunnels ($u = 3D$).

(1) Horizontally aligned twin tunnels result in the maximum settlements in comparison with all other two-tunnel arrangements.

(2) The interaction between horizontal twin tunnels in SC has a negligible effect on settlements for intermediate distances of more than $3D$.

(3) For triplet configuration, the construction order plays a very important role in the settlements. The sooner the top tunnel is constructed, the lesser would be the ground settlements.

(4) Triplets with Top-Left-Right sequence result in about 22.4% and 36.9% lesser settlements than the equivalent horizontal twins with intermediate distance of $3D$ and the Left-Right-Top sequence, respectively.

7. Future Work

This research provides a thorough knowledge of deformation patterns due to different tunnel arrangements and

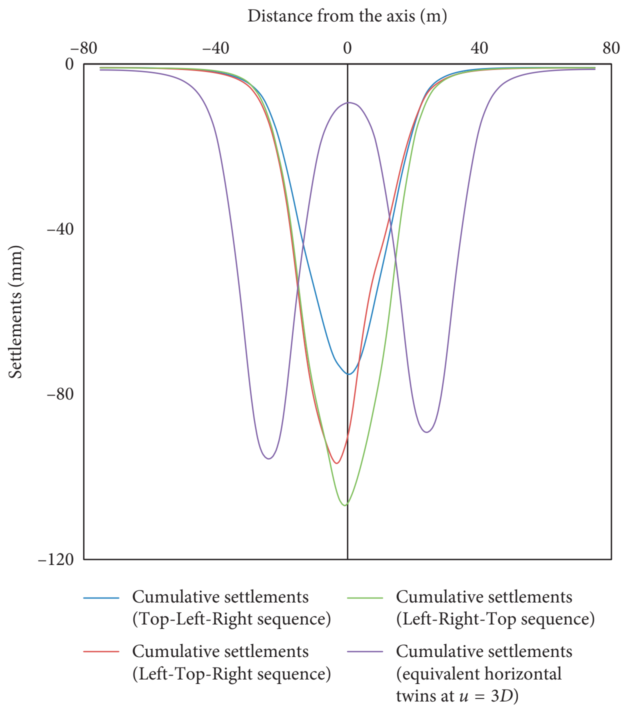


Figure 12: Settlement comparison of equivalent horizontal twin tunnels and the triplet configuration.

construction sequences. But as the $2D$ analysis was used in the study, it is recommended to perform the $3D$ analysis as well to provide a better and accurate picture of the overall deformations produced.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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