

Prediction of Ground Settlement Induced by The Construction of Twin Piggy Back Tunnels

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Abstract: *The construction of subway tunnels represents an effective solution to address transportation demands in large cities. During the planning, design, and construction stages, subway tunnels in urban areas are often arranged as two closely spaced parallel tunnels to facilitate efficient operation. However, the close spacing of twin tunnels induces mechanical interactions between them, which alter the displacement of the surrounding soil and affect both the magnitude and distribution of ground settlement. In this study, the finite element method was employed to predict and analyze the settlement trough induced by the construction of piggyback twin tunnels. The results demonstrate that piggyback twin tunnel excavation produces a larger settlement trough compared with single-tunnel excavation. In particular, the findings reveal that the construction sequence of the two tunnels significantly influences the displacement profile of the settlement trough. Specifically, the second tunnel is excavated within a soil mass that has already been disturbed and weakened by the excavation of the first tunnel, resulting in a volume loss that differs from that of the first tunnel. This study also investigates the key parameters affecting the ground settlement trough, including construction sequence, volume loss, tunnel spacing, and tunnel depth. These findings provide valuable insights for the planning, design, and construction of subway tunnels in urban environments.*

Keywords: *twin tunnels; finite element method; twin piggyback tunnel; ground settlement*

1. Introduction

The construction of subway tunnels in urban environments is widely recognized as an effective strategy to meet increasing transportation demands. Tunnel construction in soft ground often leads to ground settlement, which has been extensively studied by numerous researchers. Notable contributions in this field include the works of Peck (1969), Attewell et al., (1986), New and O'Reilly (1991), and Mair and Taylor (1997). These studies have formed the foundation for widely applied settlement prediction methods. The authors employed a variety of approaches, including analytical methods, field observations, experimental investigations, and numerical simulations, to model and understand settlement behavior. A key focus of these studies has been the characterization of the ground surface settlement trough induced by the excavation of a single tunnel. It has been shown that the horizontal profile of the surface settlement immediately following tunnel construction can be effectively represented by a Gaussian distribution curve. To enhance operational efficiency and capacity, contemporary subway systems frequently adopt twin tunnel configurations, with two parallel tunnels positioned in close proximity. The geometric arrangement of these tunnels is determined by project-specific design and construction conditions. According to Addenbrooke and Potts (2001), Hunt (2005), Divall (2013), Do et al., (2014), Islam and Iskander, (2021), Divall et al. (2023), three primary configurations are typically employed: (1) Side by side, twin tunnels aligned along the same horizontal axis; (2) Piggy back, twin tunnels positioned vertically along the same vertical axis; and (3) offset, twin tunnels offset in both horizontal and vertical directions.

Despite extensive research on ground settlement induced by tunnel excavation, the majority of studies have focused on single tunnel configurations, while investigations involving twin tunnel systems remain relatively limited. Some researchers have employed experimental techniques and finite element modeling to analyze settlement behavior in horizontally aligned twin tunnels, Thai Do et al., (2022), Hu et al., (2024), Islam and Iskander, (2025), whereas others have examined vertically stacked tunnel arrangements, Islam and Iskander, (2023). However, a critical factor that is often overlooked in the existing literature is the influence of tunnel construction sequence. Previous studies have demonstrated that ground settlement induced by two parallel shallow tunnels is often greater than the simple summation of settlements caused by each tunnel individually (Addenbrooke and Potts, 1996, Suwansawat and Einstein, 2007).

Studies have further showed that the total surface settlement comprises the superposition of settlements from the individual tunnels along with an additional component resulting from tunnel–tunnel interaction effects. Moreover, it has been observed that in twin tunnel configurations with tunnels aligned along the same horizontal axis, the resulting surface settlement profiles are generally asymmetric, reflecting the influence of interaction between the tunnels.

In this study, the finite element method (FEM) is applied using the Plaxis2D to predict ground settlement resulting from the construction of twin piggy back tunnels. The analysis considers several key parameters, including construction sequence, volume loss, inter-tunnel spacing, and tunnel depth. Particular emphasis is placed on assessing the effect of construction sequence on surface settlement in a piggy back tunnels.

2. Material and methods

In this study, to predict ground settlement caused by the construction of two parallel tunnels with the same vertical axis, these two tunnels have the same cross-sectional shape, which is circular, with the same dimensions and technical parameters including: diameter $D = 6.65$ m; tunnel lining thickness $d = 0.3$ m; tunnel lining elastic modulus $E = 35$ GPa, Poisson's ratio $\nu = 0.15$, the depth from the surface ground to the center of the upper and lower tunnels is $Z_{Up} = 2D$ and $Z_{Lo} = Z_{Up} + L$, respectively, in which D is the tunnel diameter, the distance between the centers of the two tunnels is $L = 2D$, the two tunnels are built through the clay layer. The physical and mechanical parameters of the soil layer are shown in Tab. 1. The simulation diagram of the construction of the twin piggyback tunnels is shown in Fig. 1.

Tab. 1. The physical and mechanical parameters of the soil layer

Parameters	Symbols	Value	Unit
Unit weight	γ	19.50	(kN/m ³)
Triaxial loading Young's modulus	E_{50}^{ref}	32500	(kN/m ²)
Oedometric loading Young's modulus	E_{oed}^{ref}	32500	(kN/m ²)
Unloading–reloading Young's modulus	E_{ur}^{ref}	97500	(kN/m ²)
Cohesion	c_{ref}	7.0	(kN/m ²)
Angle of friction	ϕ	20.5	(°)
Poisson's ratio	ν	0.28	-

The method used to predict the ground settlement curve caused by the construction of two parallel tunnels with the same vertical axis, the author used the finite element method, through Plaxis2D, a method that allows the analysis of the displacement of the compacted soil around the tunnel and the ground surface, according to Kunst, (2017), Bousbia, (2024).

The initial stress condition in the model uses the gravity force method, in this problem the vertical stress σ_v (kN/m²) is determined through the volume weight of the soil layer, according to the following formula:

$$\sigma_v = Z \cdot \gamma \quad (1)$$

In which: Z - depth of the location where the stress is determined (m); γ - unit weight of the soil layer (kN/m³);

Horizontal stress σ_h (kN/m²) is determined through the horizontal pressure coefficient K_0 , according to the following formula:

$$\sigma_h = K_0 \cdot \sigma_v \quad (2)$$

In which: K_0 - horizontal pressure coefficient;

Coefficient K_0 is determined through the value of internal friction angle of the soil layer ϕ (°), according to the following formula:

$$K_0 = 1 - \sin\phi \quad (3)$$

During tunnel construction using a tunnel boring machine (TBM), ground movement primarily results from the inward displacement of soil toward the tunnel face, driven by stress relief, which ultimately

leads to ground loss (Wang et al., 2022, Le et al., 2023, Rigamonti et al., 2025). The extent and nature of this ground loss depend significantly on the tunneling method employed—whether open excavation or closed-face tunneling using a TBM. According to Mair and Taylor (1999), the principal sources of ground loss include face instability, radial ground displacement toward the shield, annular gap at the shield tail, deflection of tunnel lining segments, and subsequent ground consolidation.

Under the assumption of plane strain conditions and considering the tunnel cross-section, ground loss is commonly characterized by tunneling engineers using two parameters: tunnel volume loss ($V_{l,t}$) and soil volume loss ($V_{l,s}$). The soil volume loss, $V_{l,s}$ is defined as the ratio of the volume of the ground settlement trough per unit length of tunnel (V_s) to the final cross-sectional area of the tunnel (V_0):

$$V_{l,s} = \frac{V_s}{V_0} \times 100, (\%) \quad (4)$$

In experimental, analytical, and numerical studies, ground loss is commonly represented by the tunnel volume loss, $V_{l,t}$ defined as the ratio of the volume of ground loss at the tunnel perimeter (ΔV) to the original tunnel cross-sectional area (V_0):

$$V_{l,t} = \frac{\Delta V}{V_0} \times 100, (\%) \quad (5)$$

In both experimental and analytical modeling approaches, ground loss is typically simulated by assuming that tunnel excavation induces radial ground displacement toward the tunnel perimeter. This inward movement results in a reduction of the effective tunnel cross-sectional area relative to the initially excavated area. The parameter $V_{l,t}$ is thus used to quantify the magnitude of tunnel contraction and serves as a key input in modeling ground deformation associated with tunnel construction. The magnitude of volume loss during tunnel excavation is influenced by several factors, including the geological conditions (e.g., soil type), the tunneling method employed, and the skill level of the contractor. According to Mair and Taylor (1999), In stiff clays, such as London Clay, volume losses associated with open-cut tunnelling techniques generally range between 1% and 2%; When employing shotcrete linings e.g., the New Austrian Tunnelling Method, NATM in London Clay, ground movements can be effectively controlled, with volume losses typically between 0.5% and 1.5%; Earth Pressure Balance (EPB) machines are capable of achieving effective control of ground settlement. In favorable conditions, EPB tunneling can limit volume loss to approximately 0.5% in soft sands and clays, thereby minimizing surface deformation and associated risks in urban environments. Under mixed ground conditions, EPBs and compactors may exhibit increased volume losses due to greater complexity in face stability and soil response. In this study, the authors used a volume loss of 0.5%.

The size of the numerical model significantly influences both computational efficiency and the accuracy of simulation results. According to Oteo and Sagaseta (1982), the horizontal distance from the tunnel center to the vertical boundary of the model should be at least 10 times the tunnel diameter to minimize boundary effects. This recommendation has been widely adopted in subsequent studies to ensure that boundary constraints do not interfere with the simulation of tunnel-induced ground deformations. In the present study, the model dimensions were selected in accordance with these guidelines. Specifically, the horizontal distance from the tunnel center to the vertical boundary was set to 100 meters, exceeding 14 times the tunnel diameter. The overall model dimensions are 200 meters in width and 75 meters in height, as illustrated in Fig. 2.

Boundary conditions: For the boundary conditions, in this analysis, no horizontal or vertical displacements are allowed at the bottom boundary of the model. On the two vertical boundaries of the model, only vertical displacements are allowed, no horizontal displacements are allowed. Finally, the top boundary of the model allows horizontal and vertical displacements.

The steps to simulate the construction of twin piggyback tunnels include:

Step 1: Set up initial parameters, declare boundary conditions.

Step 2: Excavation and installation of the first tunnel lining.

Step 3: Imposing the volume loss for the first tunnel.

Step 4: Excavation and installation of the second tunnel lining.

Step 5: Imposing the volume loss for the second tunnel.

The simulation diagram of twin piggyback tunnels is shown in Fig. 1.

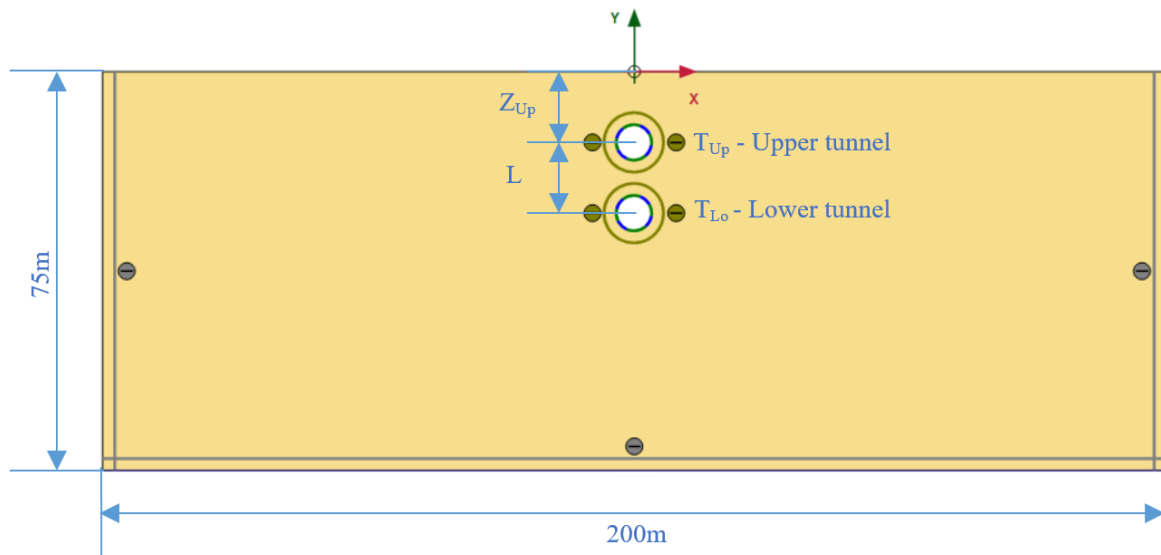


Fig. 1. Numerical simulation model illustrating the construction of twin piggyback tunnels.

3. Results and Discussions

The results of ground settlement behavior induced by the construction of piggyback twin tunnels during simultaneous excavation are examined, with particular emphasis on surface settlement under different values of volume loss. In the first case, the volume loss is assumed to be 0.5%. The corresponding settlements caused by the upper single tunnel, the lower single tunnel, and the two tunnels excavated simultaneously are illustrated in Fig. 2. The results indicate that with a volume loss of 0.5%, the maximum surface settlements induced by the upper single tunnel, the lower single tunnel, and the simultaneously excavated twin tunnels are 9.84 mm, 8.88 mm, and 15.57 mm, respectively. Similarly, Fig. 3 presents the surface settlement curves for a volume loss of 1%. The results demonstrate that with a volume loss of 1%, the maximum surface settlements induced by the upper single tunnel, the lower single tunnel, and the simultaneously excavated twin tunnels are 20.96 mm, 16.94 mm, and 32.15 mm, respectively.

In this study, volume loss values of 0.5% and 1% were investigated to compare the surface settlements induced by single tunnels and simultaneously excavated piggyback twin tunnels. The following conclusions can be drawn: a larger volume loss results in greater surface settlement; the upper single tunnel induces greater settlement than the lower single tunnel; and, finally, the piggyback twin tunnels excavated simultaneously produce larger surface settlements compared to single-tunnel excavation.

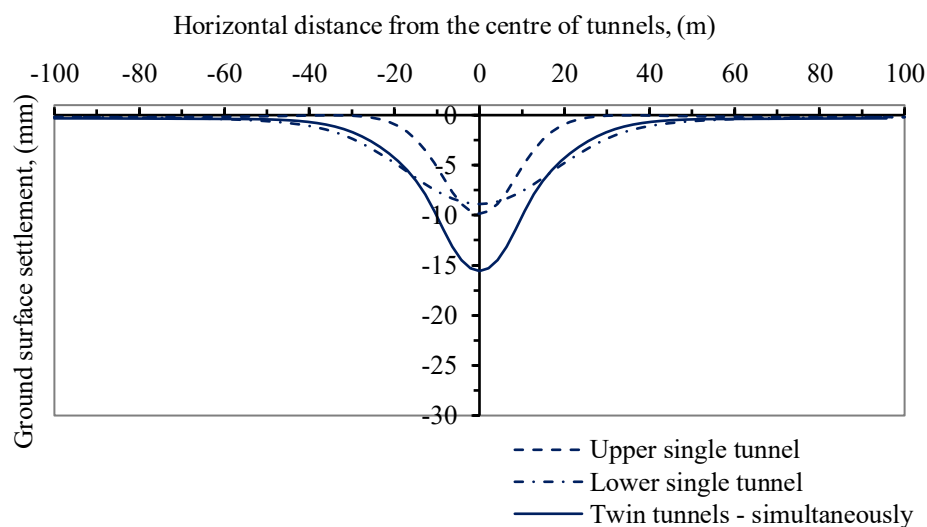


Fig. 2. Surface settlement curve for a volume loss of $VL = 0.5\%$

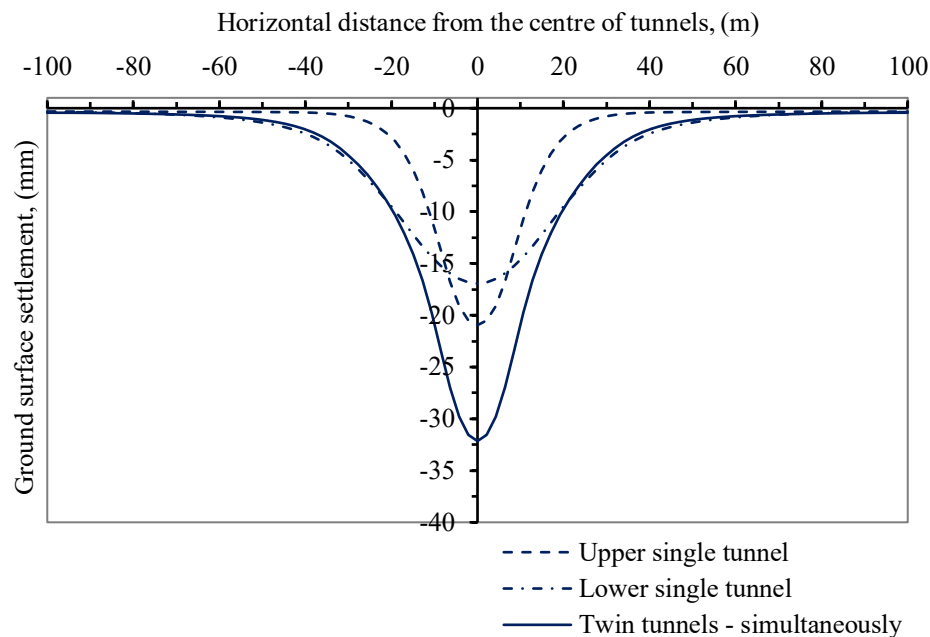


Fig. 3. Surface settlement curve for a volume loss of $VL = 1.0\%$

In practical piggyback twin tunnel construction, simultaneous excavation of the two tunnels is rare; instead, the tunnels are excavated sequentially. In this case, the second tunnel is excavated within a soil mass that has already been disturbed and weakened by the construction of the first tunnel, resulting in a different volume loss compared to that of the first tunnel. To investigate the influence of volume loss during the excavation of the second tunnel, the authors analyzed piggyback twin tunnel construction with different excavation sequences. Specifically, the first tunnel was excavated with a constant volume loss of 0.5%, while the second tunnel was assigned varying volume loss values of 1.25%, 1%, 0.75%, 0.5%, 0.25%, and 0.1%, as illustrated in Fig. 4. The results show that when the upper tunnel is excavated first with a constant volume loss of 0.5%, followed by the lower tunnel with varying volume losses of 1.25%, 1%, 0.75%, 0.5%, 0.25%, and 0.1%, the maximum surface settlements induced by the two tunnels are 25.62 mm, 22.22 mm, 18.82 mm, 15.52 mm, 12.15 mm, and 10.58 mm, respectively. Furthermore, when the lower tunnel is excavated first with a constant volume loss of 0.5%, followed by the upper tunnel with varying volume losses of 1.25%, 1%, 0.75%, 0.5%, 0.25%, and 0.1%, the maximum surface settlements induced by the two tunnels are 33.30 mm, 27.99 mm, 22.58 mm, 17.03 mm, 11.41 mm, and 8.16 mm, respectively.

The investigation of surface settlement induced by piggyback twin tunnels, in which the first tunnel is excavated with a constant volume loss of 1% and the second tunnel is excavated with varying volume loss values of 1.5%, 1.25%, 1.0%, 0.75%, 0.5%, and 0.25%, is presented in Fig. 5. The results indicate that when the upper tunnel is excavated first with a constant volume loss of 1%, followed by the lower tunnel with varying volume losses of 1.5%, 1.25%, 1.0%, 0.75%, 0.5%, and 0.25%, the maximum surface settlements caused by the two tunnels are 38.71 mm, 35.71 mm, 32.47 mm, 29.22 mm, 26.06 mm, and 22.86 mm, respectively. Furthermore, when the lower tunnel is excavated first with a constant volume loss of 1%, followed by the upper tunnel with varying volume losses of 1.25%, 1.0%, 0.75%, 0.5%, and 0.25%, the maximum surface settlements induced by the two tunnels are 44.96 mm, 39.92 mm, 34.65 mm, 29.43 mm, 24.07 mm, and 18.69 mm, respectively.

Numerous studies have focused on analyzing the influence of excavation sequence on the development of surface settlement in piggyback twin tunnel construction. Numerical simulations and experimental results (Do et al., 2022; Islam and Iskander, 2021) indicate that excavating the upper tunnel first induces greater settlement compared to excavating the lower tunnel first. In addition, observations by Addenbrooke & Potts (2001) confirmed that when the upper tunnel is excavated first, it is significantly affected by the deformations induced during the subsequent excavation of the lower tunnel. Therefore, in practice, to minimize risks and control deformations, the lower tunnel is generally preferred to be excavated first in piggyback twin tunnel construction.

In sequential piggyback twin tunnel construction, the second tunnel is excavated within a soil mass that has already been disturbed and weakened by the excavation of the first tunnel. Since the second tunnel is excavated in a stress-relieved ground, its volume loss is smaller than that of the first tunnel. As shown in

Figs. 4 and 5, when the first tunnel is excavated with a volume loss of 0.5% and the second tunnel with a volume loss of either 0.25% or 1%, the settlement induced by the lower tunnel is smaller than that induced by the upper tunnel when excavated first. Similarly, when the first tunnel is excavated with a volume loss of 1.0% and the second tunnel with a volume loss of 0.5% or 0.25%, the settlement induced by the lower tunnel is again smaller than that induced by the upper tunnel when excavated first. The results therefore demonstrate that in sequential piggyback twin tunnel construction, when the volume loss of the second tunnel is smaller than that of the first tunnel, the surface settlement outcomes are consistent with previous studies.

To further clarify the influence of the volume loss of the second tunnel, the authors investigated its effect on surface settlement, as shown in Fig. 6. In this analysis, the volume loss of the first tunnel was fixed at 1.0%, while that of the second tunnel was varied from 20% to 60% of the first tunnel's volume loss. The results indicate that when the upper tunnel is excavated first with a volume loss of 1% and the lower tunnel is excavated second with volume losses equal to 20%, 30%, 40%, 50%, and 60% of the first tunnel's volume loss, the corresponding maximum surface settlements are 22.34 mm, 23.40 mm, 24.55 mm, 26.06 mm, and 27.26 mm, respectively. Similarly, when the lower tunnel is excavated first with a volume loss of 1.0% and the upper tunnel is excavated second with volume losses equal to 20%, 30%, 40%, 50%, and 60% of the first tunnel's volume loss, the corresponding maximum surface settlements are 17.58 mm, 19.76 mm, 21.92 mm, 24.07 mm, and 26.24 mm, respectively.

The results of the investigation on the influence of the distance between the two tunnels on the maximum surface settlement are presented in Fig. 7. To analyze this effect in the piggyback tunnel configuration, a series of numerical analyses was conducted. In these analyses, the depth of the upper tunnel was fixed at $Z_{Up} = 2D$, where D is the tunnel diameter. The vertical distance between the two tunnels was varied by adjusting the depth of the lower tunnel accordingly. Two excavation sequences for piggyback twin tunnels were examined: (1) the upper tunnel excavated first followed by the lower tunnel, and (2) the lower tunnel excavated first followed by the upper tunnel.

The results show that for excavation sequence (1), where the upper tunnel is excavated first with a volume loss of 1.0% and the lower tunnel is subsequently excavated with a volume loss of 0.3%, the maximum surface settlements corresponding to tunnel spacings of 1.5D, 2.0D, 2.5D, 3.0D, and 3.5D are 22.75 mm, 23.40 mm, 23.81 mm, 24.08 mm, and 24.31 mm, respectively. For excavation sequence (2), where the lower tunnel is excavated first with a volume loss of 1.0% and the upper tunnel is subsequently excavated with a volume loss of 0.3%, the maximum surface settlements for tunnel spacings of 1.5D, 2.0D, 2.5D, 3.0D, and 3.5D are 19.92 mm, 19.76 mm, 19.36 mm, 18.86 mm, and 18.45 mm, respectively, as illustrated in Fig. 7.

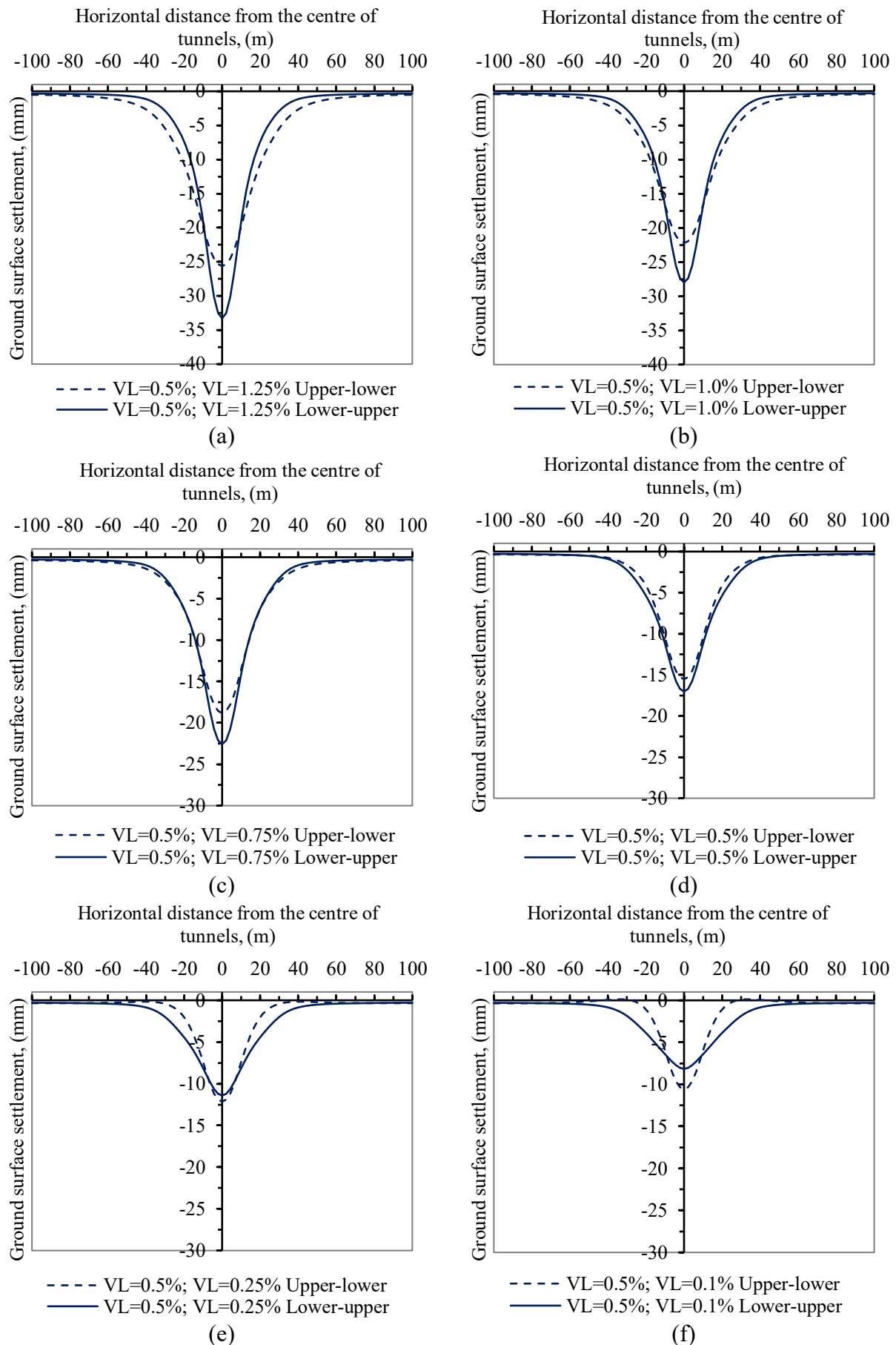


Fig. 4. Investigation of the influence of the volume loss of the second tunnel on the surface settlement when the volume loss of the first tunnel is VL= 0.5%

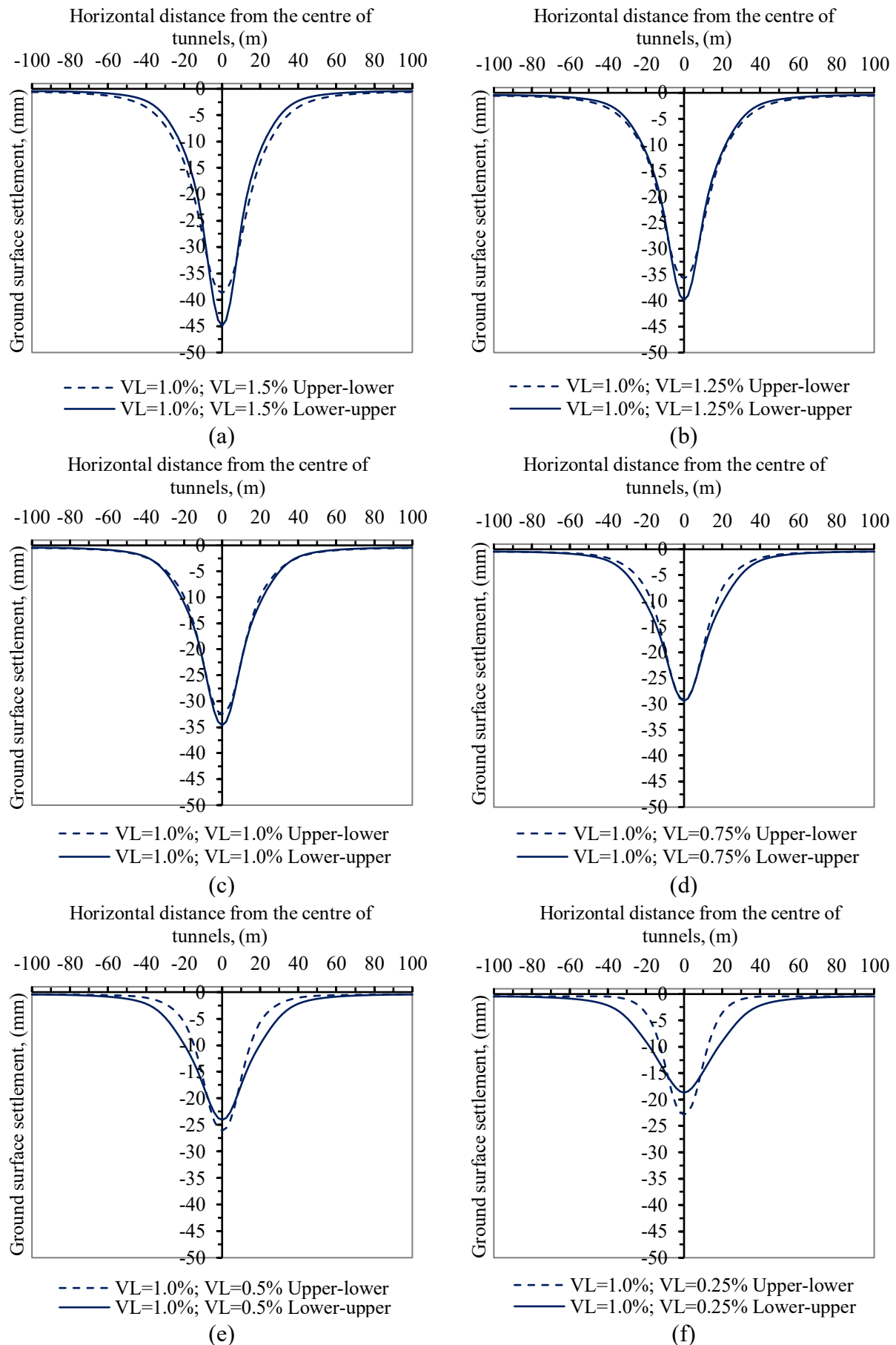


Fig. 5. Investigation of the influence of the volume loss of the second tunnel on the surface settlement when the volume loss of the first tunnel is $VL = 1.0\%$

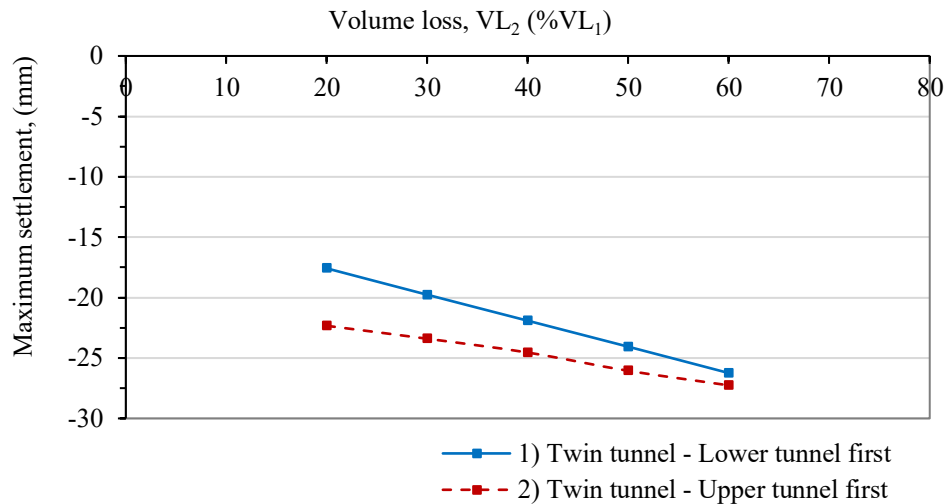


Fig6. Influence of the volume loss of the second tunnel (VL_2) on the maximum surface settlement.

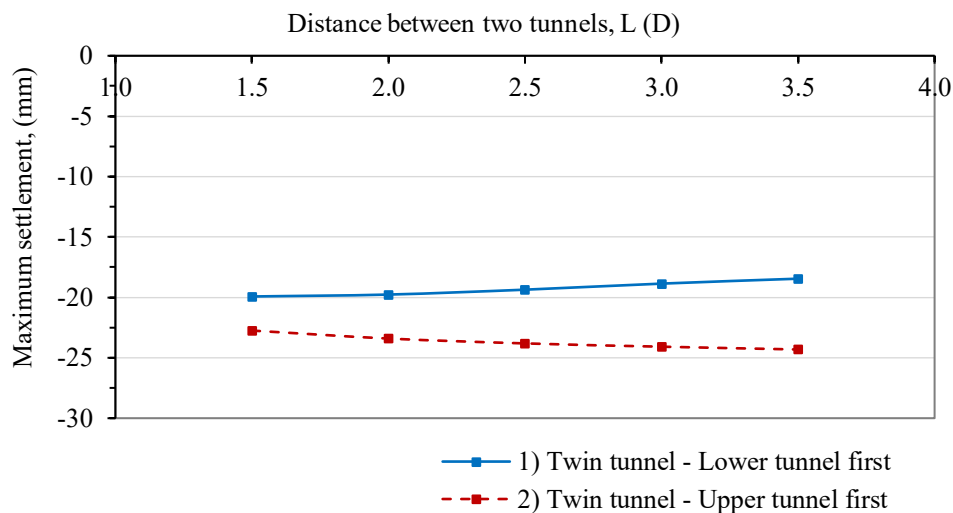


Fig. 7. Influence of the distance between the two tunnels $L(D)$ on the surface settlement when the volume losses of the first and second tunnels are $VL_1 = 1.0\%$ and $VL_2 = 0.3\%$, respectively.

The influence of tunnel depth on surface settlement was investigated, and the results are presented in Fig. 8. In this study, a series of numerical simulations was conducted in which the vertical spacing between the two tunnels was kept constant at $L = 2D$, where D is the tunnel diameter. The depth of the upper tunnel was varied with $Z_{Up} = 1.5D, 2.0D, 2.5D, 3.0D$, and $3.5D$, corresponding to the depths of the lower tunnel $Z_{Lo} = 3.5D, 4.0D, 4.5D, 5.0D$, and $5.5D$, respectively. Two construction sequences were examined: (1) the upper tunnel excavated first followed by the lower tunnel, and (2) the lower tunnel excavated first followed by the upper tunnel.

The results indicate that for excavation sequence (1), where the upper tunnel is excavated first with a volume loss of 1.0% and the lower tunnel is subsequently excavated with a volume loss of 0.3% , the maximum surface settlements corresponding to upper tunnel depths of $1.5D, 2.0D, 2.5D, 3.0D$, and $3.5D$ are 24.48 mm, 23.40 mm, 22.14 mm, and 21.10 mm, respectively. For excavation sequence (2), where the lower tunnel is excavated first with a volume loss of 1.0% and the upper tunnel is subsequently excavated with a volume loss of 0.3% , the maximum surface settlements for upper tunnel depths of $1.5D, 2.0D, 2.5D, 3.0D$, and $3.5D$ are 20.16 mm, 19.76 mm, 19.17 mm, 18.32 mm, and 17.78 mm, respectively, as shown in Fig. 8.

In studies investigating the influence of tunnel spacing and tunnel depth on ground settlement induced by piggyback twin tunnels, the construction sequence in which the lower tunnel is excavated first leads to smaller ground settlement compared with the sequence where the upper tunnel is excavated first.

This finding is consistent with previous studies by Addenbrooke & Potts (2001), Do et al. (2014), and Islam & Iskander (2021).

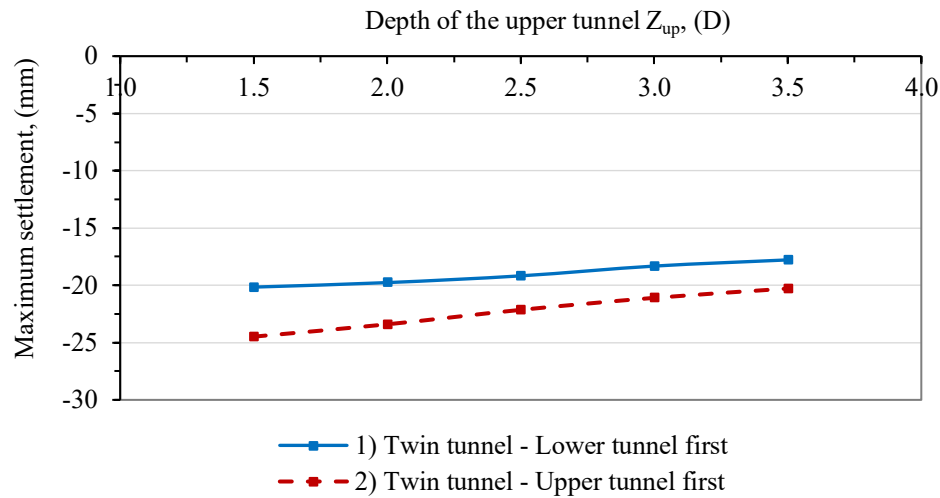


Fig. 8. Influence of the depth of the upper tunnel $Z_{up}(D)$ on the surface settlement when the volume losses of the first $VL_1 = 1.0\%$ and second tunnels are and $VL_2 = 0.3\%$, respectively.

4. Conclusions

This study presents the results of a series of numerical simulations aimed at predicting ground surface settlement induced by the construction of piggyback twin tunnels. The analyses investigate the influence of key parameters, including construction sequence, volume loss, tunnel spacing, and tunnel depth, on ground settlement behavior. Based on the simulation results, the following conclusions are drawn, which may provide valuable insights for engineers involved in tunnel planning, design, and construction:

For piggyback twin tunnel construction, the maximum ground settlement consistently occurs along the central axis of the tunnel alignment.

In the case of single tunnel excavations, construction of the lower tunnel induces smaller vertical displacements compared to the upper tunnel. However, the settlement trough associated with the lower tunnel is wider, indicating a broader zone of influence.

When both tunnels are excavated in the piggyback configuration, the construction sequence has a significant impact on the settlement response. Specifically:

An increase in volume loss results in larger vertical displacements for both construction sequences, whether the upper tunnel is excavated first or the lower tunnel is excavated first. Moreover, the second tunnel is excavated within a soil mass that has already been disturbed by the preceding excavation, meaning that the effective volume loss of the second tunnel differs from that of the first.

Tunnel spacing is found to have a relatively minor influence on the maximum ground settlement.

Increasing the depth of the piggyback twin tunnels leads to a reduction in the maximum ground settlement.

The subsequently excavated tunnel is constructed within a soil mass that has already been disturbed, damaged, and unloaded due to the excavation of the first tunnel, therefore, the volume loss of the second tunnel is smaller than that of the first tunnel. In studies investigating the influence of tunnel spacing and tunnel depth on ground settlement, the construction sequence in which the lower tunnel is excavated first results in smaller ground settlement compared with the sequence where the upper tunnel is excavated first.

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