



Journal of Mining and Earth Sciences

Website: <https://jmes.humg.edu.vn>



Surface settlement caused by twin stacked tunnels excavated beneath buildings



Tien Tai Nguyen^{1,2}, Thoueilles Maelle³, Vi Van Pham^{4,*}, Thuc Viet Chu⁴, Canh Van Dao⁴, Anh Ngoc Do^{1,2}, Daniel Dias³

¹ Faculty of Civil Engineering, Hanoi University of Mining and Geology, Viet Nam

² Tunnelling and Underground Space Technology Research Team (TUS), Hanoi University of Mining and Geology, Viet Nam

³ University of Grenoble Alpes, France

⁴ Electric Power University, Hanoi, Viet Nam

ARTICLE INFO

Article history:

Received 18th Aug. 2025

Revised 2nd Nov. 2025

Accepted 20th Nov. 2025

Keywords:

Building,
Surface settlement,
TBM,
Twin tunnels.

ABSTRACT

Underground construction plays a crucial role in the development of megacities by addressing key urban transportation challenges such as traffic congestion and limited parking. One of the most effective solutions to the growing global demand for efficient transportation systems is the development of underground public transit networks, particularly subways. To support the rapid expansion of such infrastructure, this study investigates the impact of twin stacked tunnel excavation on ground surface settlement through three-dimensional (3D) numerical modeling. The models were developed under various excavation scenarios, considering factors such as groundwater level, soil conditions, face pressure, and grouting pressure applied by the Tunnel Boring Machine (TBM). The Ben Thanh - Suoi Tien metro line in Ho Chi Minh City was used as a reference case study, with settlement data from the tunnel site employed to validate the numerical model. The results show that all investigated parameters significantly influence ground settlement above twin stacked tunnels. In particular, variations in water level, soil conditions, face pressure, and grouting pressure have significantly influenced the surface settlement when the upper tunnel is excavated. This indicates their critical role in ensuring ground stability and must be carefully considered during the construction process.

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*Corresponding author

E - mail: phamvanvi0410@gmail.com

DOI: 10.46326/JMES.2025.66(6).05

1. Introduction

Development of underground infrastructure construction, including subways, becomes the key solution to transportation challenges in megacities such as Hanoi and Ho Chi Minh cities. The standard design of subways is parallel twin tunnels, allowing unidirectional traffic motion per tunnel. Due to dense urbanization, tunnels are usually located in areas with existing surface structures, which may cause potential instability during tunneling.

Many studies have been conducted to understand what is happening during tunnel excavation, the effect of tunnel excavation on existing structures, including surface settlement and displacement of structures, using experimental methods (Marshall and Mair, 2011; Nguyen et al., 2013; Franza and Marshall, 2018; Khan et al., 2023), numerical analysis for the single tunnel constructed beneath existing structures (Farrell et al., 2014; Son and Cording, 2020; Alielahi and Feizi, 2021), more complex ones considering a single tunnel with piles (Shi et al., 2017; Mroueh and Shahrour, 2002), and twin tunnels and piled structures interactions (Dias and Bezuijen, 2015; Soomro et al., 2017a,b; Selemetas and Standing, 2017; Nematollahi and Dias, 2019; Huang et al., 2021; Do et al., 2021). Analytical solutions were also developed for single tunnel-piled foundation interactions (Marshall and Haji, 2015; Wang and Jia, 2013; Franza et al., 2017). The majority of these studies have focused on the impact of tunneling on the performance of pile foundations.

The present study aims to evaluate the effects of twin stacked tunnel excavation on the ground settlement using 3D numerical models. Various

parameter scenarios of soil properties, water level, face pressure and grouting pressure were investigated to determine the critical scenarios, considering the existence of buildings. A section of the Ben Thanh - Suoi Tien metro line has been used as the case study in this research (Figure 1) (HUP, 2016). The Hardening Soil (HS) constitutive model was adopted to represent the real behavior of the soil layers. After validating the numerical model with settlement data from the real tunnel project, a numerical investigation is performed to highlight the effects of other key parameters influencing ground surface settlement, such as water level, face pressure, and grout pressure. The results indicate strong effects of these parameters on the settlement-induced twin stacked tunnels and they should be considered during the construction.

2. Numerical model

2.1. Numerical model of the twin stacked tunnels

A 3D numerical model of twin stacked tunnels beneath surface buildings was developed using finite element method (FEM) software, Plaxis 3D (Figure 3). The centerlines of the lower and upper tunnels are located at depths of -24.3 m and -13.5 m, respectively, from the ground surface. The properties of the twin tunnels, surrounding soil, and surface buildings used in the model are detailed in Tables 1 through 4. The groundwater table is positioned at -2 m, and drained conditions are assumed for the analysis. The TBM shield is modeled using plate elements, while the tunnel linings are represented by solid elements. A contraction value is applied to

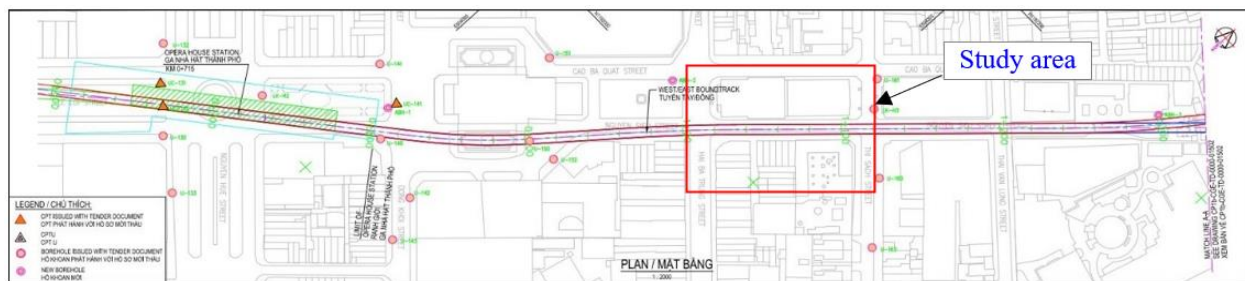


Figure 1. Study site of the Ho Chi Minh's metro line 1 (HUP, 2016).

simulate the ground convergence caused by the conicity of the TBM shield. Consistent with actual construction practice, the excavation sequence in the model assumes the lower tunnel is excavated first, followed by the upper tunnel. There are 10 buildings in the modelling area, with heights ranging from 6 m to 36 m. As these buildings were built before 1975, it was assumed that the 3 m deep would serve as the foundation. Figure 2 shows the position of each building (using Cadmapper). To simplify, the buildings (Table 4) are only modelled by floors and walls using the plate elements. The negative interface presents an interaction between buildings and soil. The model dimensions are 116 m in width, 47 m in height, and 110 m in the longitudinal direction. The top boundary of the model is free, the bottom is fully fixed, and the four vertical sides are constrained in the horizontal direction. The mesh is automatically generated using 10-node triangular elements, which adapt to the geometry of the model to ensure accurate representation. Figure 3 illustrates the mesh generated for the model. As shown in Figure 3, the mesh around the tunnels and the building foundations was created smaller. In total, 187,316 nodes and 108,466 elements were generated in the model.

The construction process of the tunnel in longitudinal direction is divided into sections and stages. As instructed in the Manual of Plaxis 3D for the TBM tunnel excavation, the first section of 40 m long in the model is excavated in one stage using the contraction parameter, which means the volume loss induced by the tunnel excavation, to simulate the 3D process. The purpose is to eliminate boundary effect on the numerical model. After that, the tunnel excavation is conducted by a cycling procedure. In each cycle, the tunnel advances by a length of 1.2 m corresponding to the length of one segmental tunnel lining ring. A contraction parameter of 0.88% is adopted based on the design dimensions of the TBM, and it is attached to both twin tunnels. The grouting pressure of 220 kN/m² and 380 kN/m², and the face pressure of 160 kN/m² and 320 kN/m², were attached for the upper and lower tunnels, respectively, based on field measurements at the Hochiminh subway project – Metro line 1.

2.2. Verification of numerical model

Settlement data obtained from the tunnel site of the Ben Thanh - Suoi Tien metro line were used to verify the numerical model. Figure 4 presents the scaled deformation of the whole model, which allows for imaging the behaviour of soil and buildings caused by tunnelling. The comparison of settlements in the cross-section of the tunnel is presented in Figure 5. It shows a good agreement between numerical and experimental results. The maximum surface settlement at the centerline of the twin tunnels calculated by the numerical model (25.46 mm) is slightly larger than the one measured at the tunnel site (22 mm). In the next section, the numerical simulations will be implemented to understand the effects of parameters on the ground surface settlement.

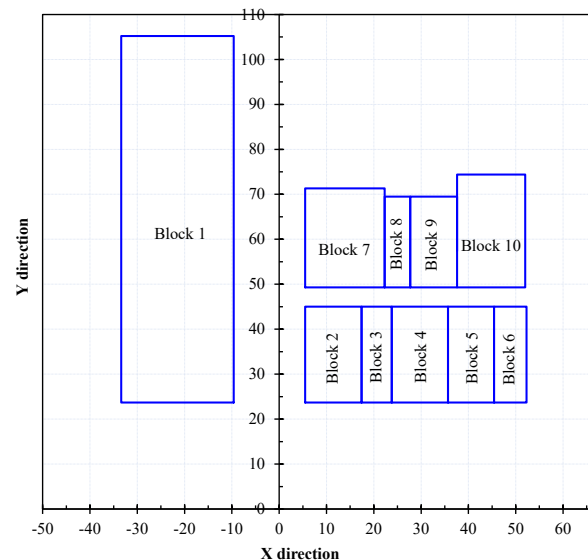


Figure 2. Position of buildings on the plan at the Ho Chi Minh City using Cadmapper software.

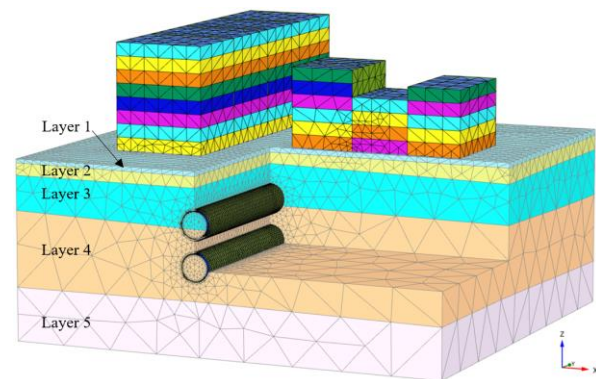


Figure 3. Mesh of the model.

Table 1. Soil parameters of the reference case.

Parameters	Symbol	Unit	Layer 1 (MC)	Layer 2 (HS)	Layer 3 (HS)	Layer 4 (HS)	Layer 5 (MC)
Density	γ	kN/m ³	19	16.5	20.5	20.5	21
Cohesion	c	kN/m ²	10	11.4	7	7	7
Internal friction angle	φ	Degree	25	17.1	31	34	35
Dilatancy	ψ	Degree	-	-	1	4	5
Poisson's ratio	ν	-	0.4	-	-	-	0.34
Young's modulus	E	kN/m ²	10000	-	-	-	85,000
Secant stiffness	E_{50}^{ref}	kN/m ²	-	5,600	15,000	27,300	-
Tangent stiffness	E_{oed}^{ref}	kN/m ²	-	4,049	15,000	27,300	-
Unloading/reloading stiffness	E_{ur}^{ref}	kN/m ²	-	11,250	45,000	81,900	-
Stiffness exponent	m	-	-	1	0.62	0.56	-

Table 2. The parameters for the tunnel lining.

Parameter	Unit	Value
External diameter (D)	m	6.65
Lining thickness (t)	m	0.3
Unit weight	kN/m ³	25
Poisson's ratio (ν)	-	0.2
Young's modulus (E)	kN/m ²	35x10 ⁶

Table 3. The number of buildings.

No	Name of building	Floor number
1	Block 1	8
2	Block 2	6
3	Block 3	2
4	Block 4	9
5	Block 5	4
6	Block 6	6
7	Block 7	6
8	Block 8	4
9	Block 9	4
10	Block 10	5

Table 4. The parameters for building.

Parameter	Foundati on slab	Floor slab	Wall
EA (kN/m)	15.0x10 ⁶	8.4x10 ⁶	10.5x10 ⁶
EI (kNm ² /m)	312.5x10 ³	54.9x10 ³	107.2x10 ³
W (kN/n)	12.5	7.0	8.75
ν	0.15	0.15	0.15

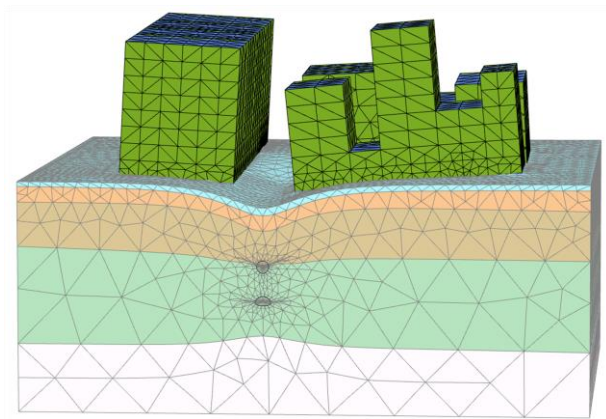


Figure 4. Deformation in the 3D model when excavating twin tunnels (scaled).

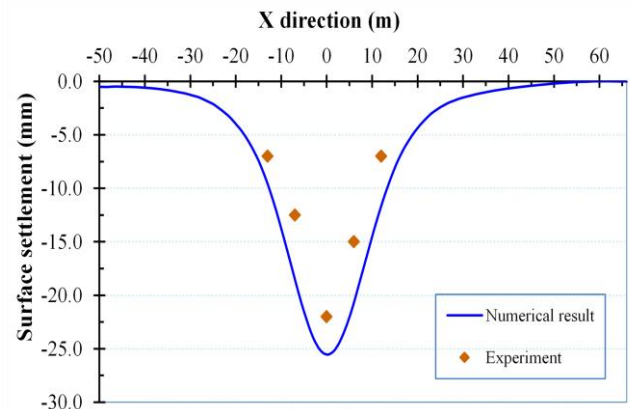


Figure 5. Surface settlement at the cross-section at Y = 23 m when excavating twin tunnel.

3. Parametric study

3.1. Effect of the groundwater level

This section examines the impact of groundwater level on surface settlement induced by the excavation of the lower tunnel, followed by the upper tunnel. Groundwater levels ranging from 2 m to 32 m below the ground surface are analyzed. All other soil and excavation parameters are kept identical to those in the reference case (Tables 1÷4).

Figure 6 illustrates the maximum ground surface settlement resulting from the excavation of the twin tunnels. The results show that groundwater level has a significant influence on settlement. Overall, surface settlement increases as the groundwater level decreases from -2 m to -32 m. The most notable changes occur when the groundwater level drops from -2 m to -17 m, especially during the excavation of the upper tunnel. This corresponds to cases where the groundwater level is still above the invert of the upper tunnel. Beyond this depth, further lowering of the groundwater level leads to only marginal increases in settlement. Figure 6 also reveals that the groundwater level has a more pronounced effect on surface settlement during the excavation of the upper tunnel compared to the lower tunnel. In other words, the shallower the tunnel, the greater the impact of the groundwater level on settlement.

Figure 7 illustrates the influence of groundwater level on the settlement measured at the crown (top) of the tunnels during the

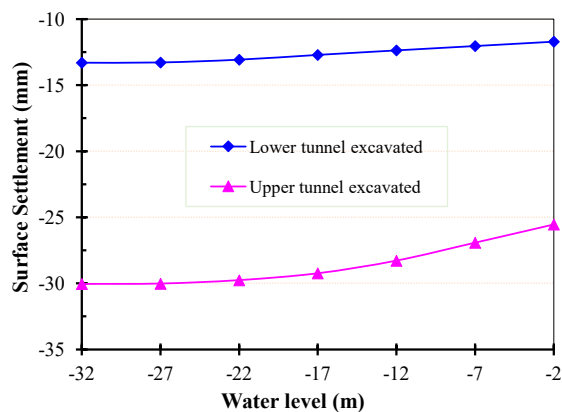
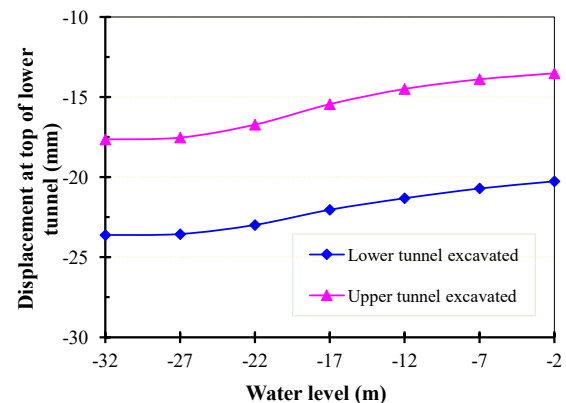


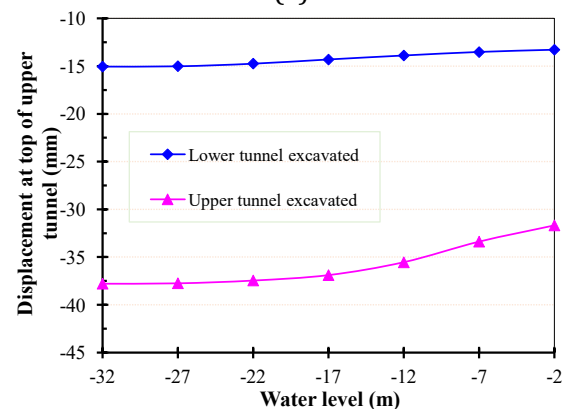
Figure 6. Effect of groundwater level on the maximum surface settlement.

excavation of each tunnel. As shown in Figure 7a, the settlement at the top of the lower tunnel increases as the groundwater level decreases. This behavior can be attributed to the reduction in pore water pressure, which increases the effective stress in the soil and allows greater soil displacement around the tunnel. The most significant increase in settlement occurs when the groundwater level ranges from -2 m to -22 m, indicating that the groundwater is above the crown of the lower tunnel. When the groundwater level drops below -22 m, the settlement changes only slightly.

During the excavation of the upper tunnel, the top of the lower tunnel exhibits a tendency to uplift. This phenomenon is caused by the upward movement of soil beneath the upper tunnel, driven by the lateral earth pressure coefficient (K_0), which is less than unity (Do et al., 2021; Do et al., 2022).



(a)



(b)

Figure 7. Effect of groundwater level on the maximum settlement measured at the crown of the tunnels.

Figure 7b shows that settlement at the top of the upper tunnel develops primarily during its own excavation. Settlement increases slightly as the groundwater level drops from -2 m to -12 m. However, once the groundwater level falls below the crown of the upper tunnel, its influence on settlement becomes negligible.

3.2. Effect of the soils

This section tests the impact of geotechnical characteristics on ground surface settlement over twin stacked tunnels. Table 5 shows the minimum, maximum, and average values of soil parameters for layers 2÷4. Three scenarios are adopted, in which the minimum, average, and maximum values are used in Scenarios 1, 2, and 3, respectively. It should be noted that these soil parameters are derived from experimental data obtained from the Ben Thanh - Suoi Tien metro

line project (HUP, 2016). All other parameters of the numerical model were taken from the reference case (Tables 1, 2, 3, and 4). The results of the ground surface settlement are presented in Table 6.

When the lower tunnel is excavated first, the reduction in soil strength in the considered scenarios of soils results in greater surface settlements. This is expected, as the lower tunnel is entirely situated within soil layer 4. However, once the subsequent upper tunnel is excavated, the results in Table 6 show an increase in surface settlement despite an increase in the soil stiffness in scenario 3 compared to the one in scenario 2. At first glance, it may seem unreasonable that greater surface settlement occurs when the upper tunnel is excavated in stiffer soil conditions. This phenomenon can be explained by the post-excavation stress redistribution around the tunnel. When the coefficient of lateral earth

Table 5. Scenarios of soil's properties.

Parameters	Symbol	Unit	Values	Layer 2 (HS)	Layer 3 (HS)	Layer 4 (HS)
Density	γ	kN/m ³	Min	16.5	20.5	20.5
			Average			
			Max			
Cohesion	c	kN/m ²	Min	10.5	7	7
			Average	11.4		
			Max	12.2		
Internal friction angle	φ	Degree	Min	17.0	30	32
			Average	17.1	31	34
			Max	17.2	33	35
Dilatancy	ψ	Degree	Min	0	0	2
			Average		1	4
			Max		3	5
Secant stiffness	E_{50}^{ref}	kN/m ²	Min	3,200	7,200	19,200
			Average	5,600	15,000	27,300
			Max	8,000	22,800	35,400
Tangent stiffness	E_{oed}^{ref}	kN/m ²	Min	2,360	7,200	19,200
			Average	4,049	15,000	27,300
			Max	5,737	22,800	35,400
Unloading/reloading stiffness	E_{ur}^{ref}	kN/m ²	Min	6,500	21,600	57,600
			Average	11,250	45,000	81,900
			Max	16,000	68,400	106,200
Stiffness exponent	m		Min	1	0.66	0.60
			Average		0.62	0.56
			Max		0.58	0.52

Table 6. Effect of soil properties on the ground surface settlement.

Tunnel	Surface settlement (mm)	
	Lower tunnel excavated	Upper tunnel excavated
Scenario 1	-12.97	-24.56
Scenario 2	-12.13	-25.55
Scenario 3	-12.12	-28.02

pressure (K_0) is less than unity, the soil above the top and below the bottom of the tunnel tends to move inward toward the tunnel center, while the soil on the sides moves outward. In softer soils, this behaviour leads to greater vertical settlements at the preceding lower tunnel crown and more pronounced upward displacement at the tunnel bottom (Figure 8a). During the excavation of the lower tunnel, the soil above the tunnel experienced a certain relaxation of stress and strain. The larger the relaxation is expected in softer soil scenarios. Subsequently, when the upper tunnel is excavated in the post-released soil medium, deformation/displacement induced in the soil surrounding the upper tunnel could be smaller in softer soil scenarios and therefore smaller settlement (Figure 8b).

3.3. Effect of the face pressure

In this section, the effect of the face pressure of the TBM on the ground surface settlement was studied. The face pressures were assumed to vary from 80 kN/m² to 240 kN/m² for the upper tunnel and from 240 kN/m² to 400 kN/m² for the lower tunnel. Based on that, 9 cases of twin tunnels' face pressure are considered as presented in Table 7. The maximum settlement is presented in Figure 9.

During the excavation of the preceding lower tunnel, the surface settlement decreases gradually with increasing face pressure and reaches a minimum at 320 kN/m². When the face pressure continuously increases, an increase in surface settlement is, however, observed. The same phenomenon is seen during the excavation of the upper tunnel, with the optimum face pressure at which the minimum settlement is obtained being nearly 180 kN/m². The existence of an optimum face pressure where the surface settlement reaches the minimum value could be

concerned to the immediate and consolidation settlements during the tunnel excavation.

Immediate settlements occur both ahead of and shortly after the tunnel face passes, primarily due to stress relaxation in the surrounding soil caused by the excavation process. As observed by Kim et al. (2018), these settlements begin in front of the tunnel face and generally decrease with increasing face pressure. In contrast, immediate settlements behind the tunnel face—particularly just after the cutter head passes—exhibit a different pattern. As face pressure increases from low levels, these settlements initially decrease, reaching a minimum at an optimal face pressure. However, beyond this point, further increases in face pressure lead to a rise in immediate settlements behind the tunnel face (Kim et al., 2018).

Consolidation settlements, on the other hand, are influenced by variations in effective stress in the vicinity of the tunnel. A critical face pressure exists at which these settlements reach their minimum. Initially, as face pressure increases, consolidation settlements decrease. However, when the face pressure exceeds the critical value, the settlements begin to increase again. This reversal is likely due to the formation of a yield zone around the tunnel face, caused by excessive pressure from the shield machine's chamber (Kim et al., 2018).

At the final or steady-state condition, the total surface settlement observed in this study is the combined result of both immediate and consolidation settlements. These two components exhibit similar trends and are both dependent on tunnel face pressure. The same pattern was observed in the tunnel case reported by Kim et al. (2018). Based on these findings, face pressures of approximately 320 kN/m² and 180 kN/m² are, respectively, recommended for the lower and upper tunnel (Figure 9).

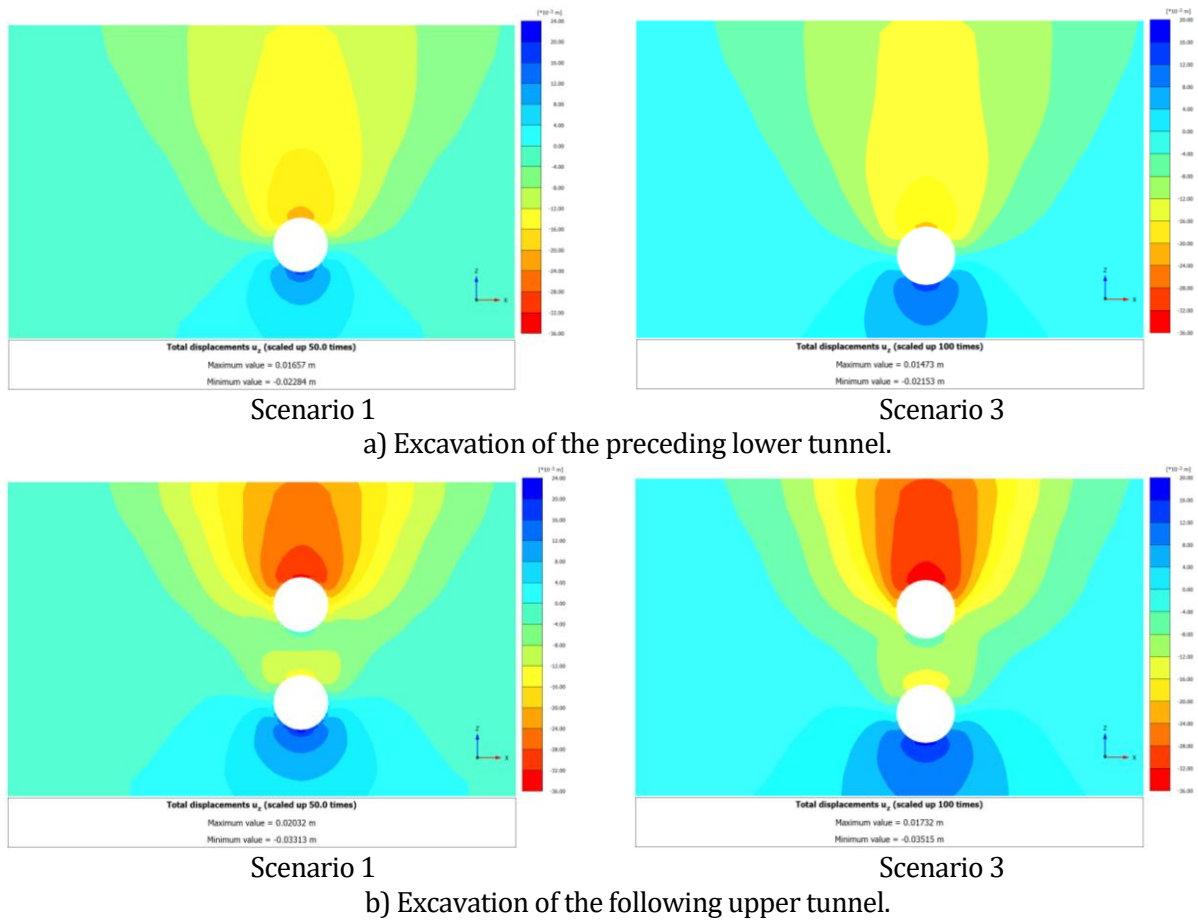
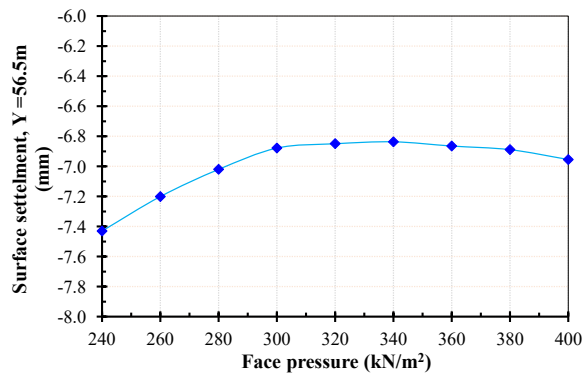


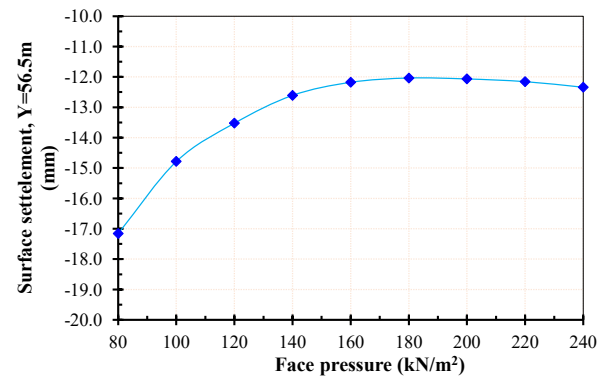
Figure 8. Effect of soil properties on soil displacement around tunnels.

Table 7. Studied cases of face pressure.

Face pressure (kN/m ²)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
The Upper Tunnel	80	100	120	140	160	180	200	220	240
The Lower Tunnel	240	260	280	300	320	340	360	380	400



a) Lower tunnel excavation.



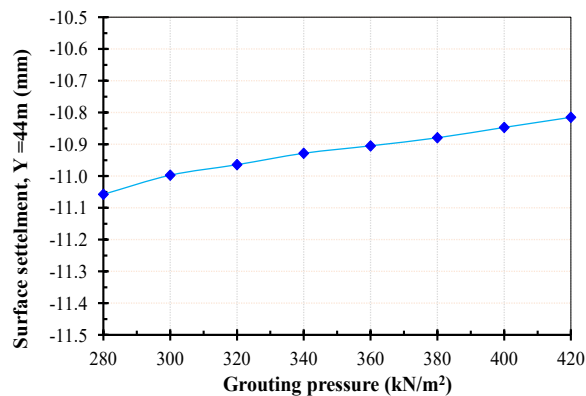
b) Upper tunnel excavation.

Figure 9. Effect of face pressure on maximum surface settlement when the tunnel excavated.

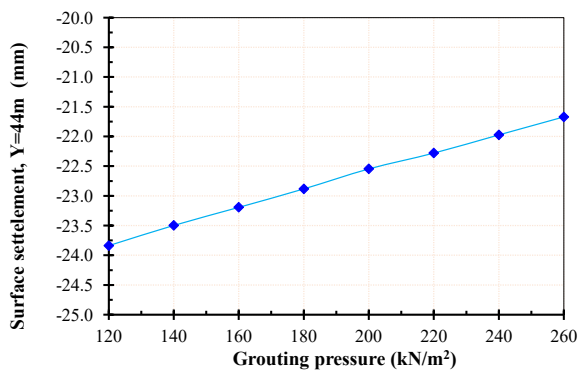
3.4. Effect of the grouting pressure

Grouting pressures are assumed to range from 120 kN/m² to 260 kN/m² for the upper tunnel and from 280 kN/m² to 420 kN/m² for the lower tunnel. In total, eight grouting pressure scenarios are investigated (see Table 8). All other parameters are kept consistent with the reference case (Tables 1÷4).

Figure 10 illustrates the relationship between maximum surface settlement and grouting pressure during the excavation of the preceding lower tunnel (Figure 10a) and the subsequent upper tunnel (Figure 10b). The results demonstrate a strong dependence of surface



a) Lower tunnel.



b) Upper tunnel.

Figure 10. Effect of grout pressure on surface settlement ($Y = 44$ m) when the tunnel excavated.

settlement on grouting pressure of both the lower and the upper tunnels. Generally, the greater the grouting pressure, the smaller the surface settlement. The variation of grouting pressure has a more significant effect on the surface settlement during the excavation of the shallower, upper tunnel. Indeed, Figure 10a shows a slight decrease in surface settlement (0.23 mm) when grouting pressure in the lower tunnel increases from 280 kN/m² to 420 kN/m². Nevertheless, surface settlement significantly changes (2.2 mm) when grouting pressure varies from 120 kN/m² to 260 kN/m² in the upper tunnel (Figure 10b).

4. Conclusion

In this study, 3D finite element simulations have been performed to investigate the surface settlement developing during the excavation of twin stacked tunnels beneath high buildings. Conditions of Ben Thanh - Suoi Tien metro line in Ho Chi Minh city have been adopted as a reference case, and settlement data from the tunnel site was used to verify the numerical model. A numerical parametric study was conducted to highlight the effect of groundwater level, soil condition, face pressure and grouting pressure. Some major conclusions can be drawn as follows:

- The water level significantly affects surface settlement when twin tunnels are excavated. The shallower the tunnel, the greater the influence of groundwater.
- The absolute maximum surface settlements were slightly increased when the lower tunnel was excavated in layer 3, which has the values from maximum to minimum. While the surface settlement has tended to the opposite when the upper tunnel was excavated, it means the absolute maximum surface settlement is the largest, with a maximum value of soil, and this one is the smallest, with a minimum value of soil.
- When the tunnel is embedded in multilayer soils, settlement induced by the tunnel excavation can be different from that of a tunnel located in a homogeneous soil medium. It could be concerned

Table 8. The grouting pressure scenarios.

Grout pressure (kN/m ²)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
The Upper Tunnel	120	140	160	180	200	220	240	260
The Lower Tunnel	280	300	320	340	360	380	400	420

to the stronger release effect at the tunnel bottom compared to that of the tunnel top. In this study, the greater surface settlement is expected when soil stiffness is higher overall in the maximum soil property scenario.

- There is an optimal face pressure at which the surface settlement is minimum. As the face pressure increases from low values to a certain value of face pressure, these settlements gradually reduce to a minimum. However, beyond this optimal point, further increases in face pressure result in a rise in settlements. Face pressures of approximately 320 kN/m² and 180kN/m² are, respectively, recommended for the lower and upper tunnels in this case study.

- Generally, the greater the grouting pressure, the smaller the surface settlement. The variation of grouting pressure has a more significant effect on the surface settlement during the excavation of the shallower, upper tunnel.

Acknowledgements

Financial support is provided by the German Science Foundation (DFG) (Project no. 518862444) and the Vietnam National Foundation for Science and Technology Development (NAFOSTED) (Project no. DFG.105-2022.03). These supports are gratefully acknowledged.

Contributions of authors

Tien Tai Nguyen - writing, original draft, methodology, investigation, data curation, conceptualization; Thouailles Maelle - writing, original draft, investigation, data curation; Vi Van Pham - writing, original draft, review & editing, investigation, data curation; Thuc Viet Chu - writing, review & editing; Anh Ngoc Do - writing, original draft, review & editing, supervision, funding acquisition, conceptualization; Daniel Dias - writing, review & editing, supervision, conceptualization; Canh Van Dao - supervision, conceptualization.

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