

Influence of twin stacked tunnels excavation on pile behavior – A case study in Ho Chi Minh City

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Abstract: The expansion of the economy has generated a growing demand for transportation infrastructure, particularly in large metropolitan areas. The development of metro tunnel systems has emerged as an inevitable solution in such contexts, where surface space is constrained. However, constructing metro tunnels beneath areas where surface structures are already in place poses significant engineering challenges. Tunnel excavation alters the stress state within the soil mass and induces ground displacements surrounding the tunnel. These displacements subsequently propagate upward to the ground surface, resulting in surface settlement that can adversely affect the stability of superstructures as well as the performance of their foundation systems. In this study, the influence of tunnel excavation on pile foundations of surface buildings is investigated under the geotechnical conditions of the Ben Thanh–Suoi Tien metro line in Ho Chi Minh City. A numerical model representing twin stacked tunnels and a building with pile foundations was first established. The settlement results obtained from the numerical simulation were validated against field monitoring data. Subsequently, the effects of tunnel excavation on different piles of the building were examined. In addition, the influence of the relative distance between the tunnel alignment and the pile foundations was analyzed. The results indicate that, at the same relative

distance between the tunnel and the pile group (1D), the farther a pile is from the tunnel, the smaller the influence on its behavior. The greater the distance between the tunnel and the pile group, the smaller the impact. When the tunnel is more than 3D away from the pile group, the influence becomes negligible. The outcomes provide valuable insights into soil–structure interaction during urban tunneling, thereby contributing to safer and more sustainable underground infrastructure development.

Keywords: Pile behavior, twin stacked tunnels, Ho Chi Minh.

INTRODUCTION

According to the Hanoi Transport Master Plan (Decision No. 519/QĐ-TTg, 2016), the urban railway network is planned to comprise 10 lines with a total length of up to 417.8 km by 2030, with a vision toward 2050. Similarly, under the Ho Chi Minh City Master Plan for the period 2021–2030 with a vision to 2050 (Decision No. 1711/QĐ-TTg, 2024), the urban railway network is designed to consist of 12 lines, with a cumulative length reaching approximately 510 km. A substantial portion of these urban railway lines is planned to run underground, particularly in densely built-up areas. The construction of these tunnels inevitably induces ground surface settlement, which in turn may adversely affect surface structures and their foundation.

Tunnel construction in proximity to pile foundations of existing buildings can significantly influence pile performance. This issue has been investigated using various approaches, including numerical modeling (Maji & Sundar, 2021; Lee, 2012; Surjadinata et al., 2006), analytical methods (Li et al., 2023; Abd-Elhamed, 2021; Marshall & Haji, 2015; Huang et al., 2009), and experimental studies (Lim et al., 2023; Ng et al., 2012; Selemetas, 2005; Poulos et al., 2000). The pile-tunnel interaction is primarily governed by factors such as ground displacements, soil properties, pile geometry, the relative position between the tunnel and the pile and tunneling methods. Understanding these factors is critical for ensuring both tunneling stability and the integrity of overlying structures.

The relative position of the tunnel with respect to the pile is a key determinant of pile-tunnel interaction. Studies by Jongpradist et al. (2013) and Soomro et al., (2017) demonstrated that pile lateral displacement and bending moment increase considerably when tunneling occurs within a distance of $1.5-2D$ (where D is the tunnel diameter). Conversely, Al-Omari et al. (2019) reported that when the tunnel-pile clearance exceeds $2.5D$, tunneling-induced effects on piles diminish significantly. Based on these findings, Su et al. (2025) recommend a minimum tunnel-pile clearance of $2D$ to $2.5D$ to ensure structural safety.

Soil conditions also play a crucial role in tunnel-pile interaction mechanisms. In sandy soils, piles tend to undergo pronounced lateral displacement as the tunnel face approaches, due to rapid drainage and stress redistribution leading to immediate settlement (Jacobsz et al., 2004). In contrast, tunneling in clayey soils initially causes short-term heave, followed by long-term consolidation settlement that progressively drags piles downward (Chen et al., 1999).

It is evident that tunneling under varying geological conditions results in distinct ground responses, which in turn induce different

structural behaviors in the pile foundations of existing buildings. The Ben Thanh-Suoi Tien metro line, the first urban railway constructed and operated in Ho Chi Minh City, includes a 2.6 km underground section. Existing studies (Do et al., 2021; Hieu et al., 2019; Nguyen, et al., 2023) have primarily focused on tunneling-induced ground settlement along this metro line. Lam et al. (2022) compared surface settlement predictions derived from Hardening Soil and Mohr-Coulomb soil models.

Overall, no prior research has comprehensively assessed the effects of tunneling on pile foundations of surface structures under the ground conditions of the Ben Thanh-Suoi Tien line in Ho Chi Minh City. The present study aims to evaluate tunneling-induced impacts on piles in a representative building and to examine how tunnel-pile spacing influences pile structural behavior.

NUMERICAL MODELING AND VERIFICATION

The Metro Line No. 1 (Ben Thanh – Suoi Tien) has a total length of 19.7 km with 2.6 km underground. The line was completed and put into operation in 2024. The tunnel section was excavated using the Earth Pressure Balance (EPB) shield machine, with a cutterhead diameter of 6.82 m and an outer shield diameter of 6.79 m. This section, extending 780 m from Km 0+805 to Km 1+586, comprises twin tunnels initiated at Ba Son Station (Km 1+586) at the same elevation, which gradually shift into a stacked configuration and terminate at the Opera House Station (Km 0+805). The tunnels were constructed at maximum and minimum depths of 25 m and 12 m, respectively (measured from the tunnel centerline). The geotechnical parameters of the soil layers are presented in Table 1. The outer and inner diameters of the tunnel lining are 6.65 m and 6.35 m, respectively, with a segmental ring width of 1.2 m. The mechanical properties of the tunnel lining are summarized in Table 3 (Shimizu – Maeda., 2016).

Table 1. Geotechnical properties

Parameter	BackFill	Alluvial Clay (AC)	Alluvial Sand (AS1)	Diluvial Sand (AS2)	Diluvial Clay (DC)
Unit weight, γ_{unsat} kN/m ³	19.00	16.50	20.50	20.50	21.00
Young Modulus E, kPa	10×10^3	-	-	-	85×10^3
E_{50}^{ref} , kPa	-	5,600	15×10^3	27.3×10^3	-
$E_{\text{aed}}^{\text{ref}}$, kPa	-	4,049	15×10^3	27.3×10^3	-
$E_{\text{ur}}^{\text{ref}}$, kPa	-	11.25×10^3	45×10^3	81.9×10^3	-
Cohesion, c_{ref} , kPa	10.00	11.4	1	1	1
Friction angle, ϕ (degree)	25.00	17.1	31	34	35
Dilatancy angle, ψ (degree)	0	0	1	4	5

Table 2. Input parameters of pile (embedded beam rows)

Parameter	Symbol	Unit	Value
Young Modulus	Ep	MPa	46×10^6
Unit weight	γ	kN/m ³	25
Diameter	D	m	0.3
Base resistance	Fmax	kN	309
Axial skin resistance at the pile bottom	-	kN/m	145

Table 3. Input parameters of plate element

Parameter	Unit	Lining	Pile cap	Building Frame	Floor slab
Flexural stiffness, EI	kN/m	78.75×10^3	312.5×10^3	107.2×10^3	54.88×10^3
Axial stiffness, EA	kN.m ² /m	10.5×10^6	15×10^6	10.50×10^6	8.4×10^6
Thickness, d	m	0.3	0.5	0.35	0.28
Unit weight, w	kN/ m ³	7.5	12.50	8.750	7.0
Poisson, ν		0.15	0.15	0.15	0.15
Parameters	Unit	Lining	Pile cap	Building Frame	Floor slab

In this study, the construction conditions at chainage Km 1+023 were selected as the reference case. The groundwater level at the site is -2.0 m from the ground surface. The numerical model was developed using Plaxis 2D, a finite element method (FEM)-based program. The model domain dimensions were set to 200 m in width (X-direction) and 45 m in height (Y-direction). For the boundary conditions, the bottom model was fixed in both vertical and horizontal directions, the lateral boundaries were fixed in the horizontal direction, while the top boundary was free in both vertical and horizontal directions (Plaxis - Bentley Systems, 2020).

The simulation stages are as follows:

Initial: Establishment of initial parameters and definition of boundary conditions;

Phase 1: Excavation and lining installation of the lower tunnel;

Phase 2: Application of the volume loss (VL) for the lower tunnel;

Phase 3: Excavation and lining installation of the upper tunnel;

Phase 4: Application of the volume loss (VL) for the upper tunnel.

In this study, a volume loss of VL = 0.88% was adopted, corresponding to the volumetric discrepancy between the outer diameter of the cutter head (6.82 m) and the outer diameter of the shield (6.79 m) (Plaxis 2D, Manual). The model was assumed under greenfield conditions. Figure 1 illustrates the results obtained from the numerical model compared with field measurement data. The findings

indicate that the maximum settlement predicted by the numerical model is only marginally higher than the field measurements, by approximately 6.6%, corresponding to 23.78 mm and 22.30 mm, respectively. Therefore, the numerical model can be considered a reliable tool for further parametric studies and predictive analyses.

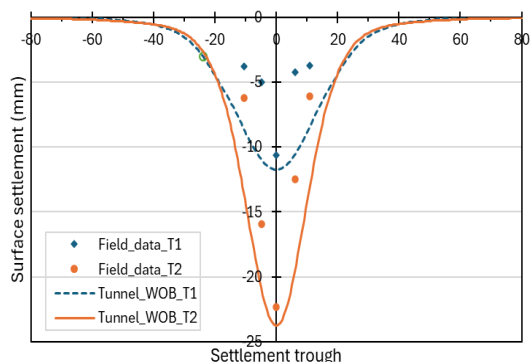


Figure 1. Comparison of settlement obtained from numerical model and field measurements

INVESTIGATION OF PILE FOUNDATION RESPONSE

As previously discussed, tunneling in densely built-up urban areas inevitably influences the performance of surface structures and their foundation. In this study, the reinforced concrete pile foundations are considered. The piles, with a diameter of 0.30 m and a length of 21.3 m, are modeled using the embedded beam element approach, and their properties are summarized in Table 2.

The superstructure is represented by a 9-story building with an overall height of 31.5 m and a single basement level extending to a depth of 3.0 m (Figure 2). The building frame, floor slabs, and pile cap are modeled as plate elements, with the corresponding input parameters listed in Table 2.

The simulation stages follow the same procedure as the reference case. However, in this scenario, the building and its pile foundation are constructed prior to the subsequent tunnel excavation. At the stage corresponding to the underground tunnel excavation, the displacements induced by the

earlier construction of the building and piles are removed (i.e., they are not carried forward into the tunneling stage).

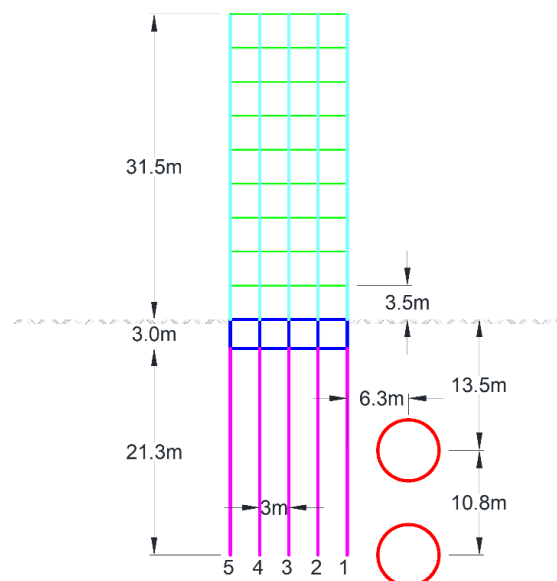


Figure 2. A case study of twin stacked tunnels, a building, and its foundation

Pile behavior under tunnel construction

In this scenario, the horizontal distance between the tunnel centerline and the building is set to 1D ($D = 6.3$ m). The response of piles 1 through 5 was analyzed in order to assess the potential impacts of tunnel excavation on pile foundations within a representative building. All other input parameters were kept consistent with those in the reference case to ensure comparability. The numerical results, in terms of the maximum and minimum bending moments and normal forces are summarized in Table 4 and illustrated in Figure 3, 4.

Prior to tunnel excavation (i.e., after pile installation), the results indicate that the bending moment in the central pile (Pile 3) was the smallest, whereas the two outer piles experienced the largest moments, exhibiting a symmetric distribution.

For Pile 1, the maximum bending moment (M_{max}) decreased from 25.47 kN after pile installation to 22.83 kN with the lower tunnel excavation and further to 15.34 kN with the upper tunnel. This trend suggests that tunnel

construction leads to a reduction in peak bending moments due to load redistribution, as the surrounding soil tends to move toward the tunnel. In Pile 2, M_{max} also dropped sharply from 12.26 kN to 2.796 kN during the upper tunnel excavation. By contrast, changes in Piles 3–5 were minor, indicating that the tunnel–pile interaction effect diminishes with increasing distance from the tunnel.

Regarding the minimum bending moment (M_{min}), Pile 1 exhibited a transition from a negative value (−6.561 kN) after pile installation to positive values (8.442 kN and 5.456 kN) during the lower and upper tunnel excavations, respectively. This reversal of moment direction

can be attributed to lateral soil movement toward the tunnel. For Piles 2–5, M_{min} remained negative, with larger magnitudes observed for piles located farther from the tunnel (e.g., Pile 5: from −25.89 kN to −30.84 kN during lower tunnel excavation, then reduced to −21.13 kN during upper tunnel excavation). These results suggest that piles farther from the tunnel are more susceptible to negative bending moments during lower tunnel excavation, while the subsequent upper tunnel excavation slightly mitigates these adverse effects.

Table 4. Internal forces and displacements of piles at a tunnel–building distance of 1D

		M_{max} (kN)	M_{min} (kN)	N_{max} (kN/m)	N_{min} (kN/m)	$U_{x,max}$ (mm)	$U_{y,max}$ (mm)
Pile 1	Building	25.47	-6.561	513.4	99.01	2.33	-24.69
	Lower tunnel	22.83	8.442	437.5	135.2	5.4	-11.59
	Upper tunnel	15.34	5.456	543.3	146.7	9.83	-11.66
Pile 2	Building	12.26	-2.702	319.295	88.74	9.93	-25.21
	Lower tunnel	4.017	-2.882	362.2	137.1	5.4	-9.01
	Upper tunnel	2.796	-1.469	393.7	150.5	9.84	-9.07
Pile 3	Building	0.1341	-0.1884	286.2	87.66	2.74	-25.43
	Lower tunnel	1.735	-8.86	343.2	119.5	5.41	-6.92
	Upper tunnel	0.9611	-5.517	356.4	126.3	9.84	-6.76
Pile 4	Building	2.763	-12.66	319.6	91.73	1.6	-25.13
	Lower tunnel	2.989	-19.83	348.8	109.6	5.41	-5.07
	Upper tunnel	2.059	-13.33	353.5	111.3	9.84	-4.42
Pile 5	Building	6.625	-25.89	514.3	106.1	2.963	-24.53
	Lower tunnel	6.08	-30.84	469	111.2	5.416	-3.45
	Upper tunnel	4.167	-21.13	458.5	109.4	9.841	-2.97

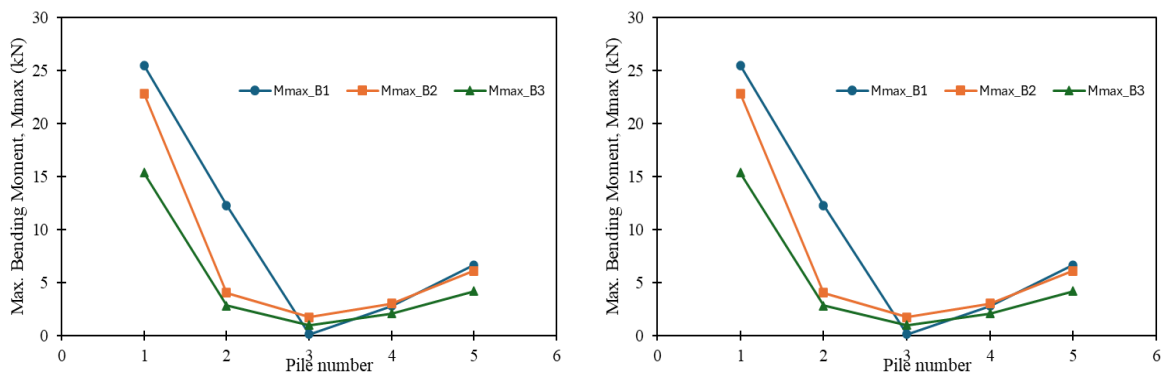


Figure 3. Max. and Min. bending moment in piles

For Pile 1, the maximum axial force (N_{max}) showed a pronounced reduction following the excavation of the lower tunnel (Fig. 4). This can be explained by the pile toe being located directly along the axis of the lower tunnel, which induced lateral displacement and load redistribution. Consequently, the axial force increased near the pile toe but decreased at the pile head. During the upper tunnel excavation, further displacement occurred along the mid-section

of Pile 1, resulting in a localized increase in axial force. For Piles 2 through 5, a similar trend was observed, yet the magnitude of change in N_{max} was substantially smaller.

After the construction of the building and its foundation, the maximum horizontal displacement ($U_{x,max}$) of Piles 1–2 was found to be symmetric with that of Piles 4–5 with respect to the central pile (Pile 3). Among all piles, the central pile exhibited the smallest lateral displacement (Fig.5).

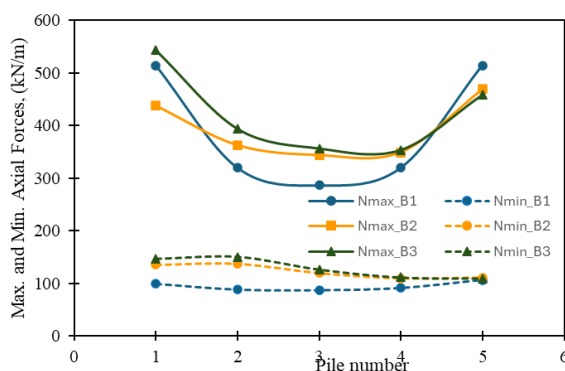


Figure 4. Max. and min. normal forces in piles

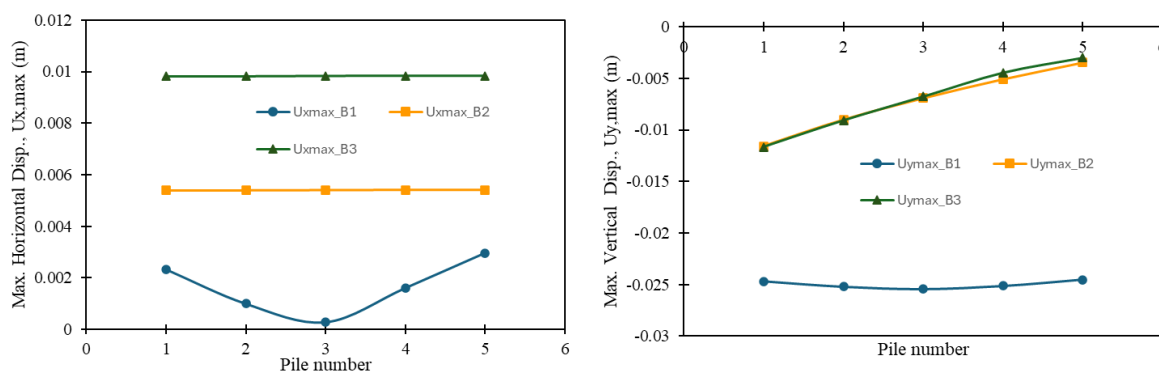


Figure 5. Maximum horizontal and vertical displacement of piles ($U_{x,max}$ and $U_{y, max}$)

Following the excavation of the lower tunnel, ground movements induced by tunneling caused all piles to displace toward the tunnel side. The $U_{x,max}$ was observed at the pile head, and the pattern was consistent across all piles (Piles 1 to 5). Subsequent excavation of the upper tunnel further amplified soil movement, resulting in additional pile displacements and an increase in $U_{x,max}$. These results emphasize the

progressive nature of pile–soil–tunnel interaction, where sequential tunneling activities significantly influence pile performance, particularly in terms of lateral stability.

The $U_{y,max}$ of the piles prior to tunnel excavation was relatively large, primarily due to the effect of structure loading. During tunnel excavation, ground settlement occurred both

around the tunnel and at the ground surface. The magnitude of pile settlement was strongly dependent on the pile's location relative to the settlement trough: Pile 5, positioned farther from the trough, exhibited smaller vertical displacements

compared with Pile 1, which was closer to the trough. In the case of the upper tunnel excavation, the influence on vertical displacements was considerably less significant, as the tunnel alignment intersected approximately at the mid-depth of the piles rather than at their toes. These results confirm that lower tunnel excavation imposes greater

effects on pile settlement, whereas the upper tunnel contributes only marginal additional displacement.

Pile behavior in relation to pile–tunnel distance

To investigate the influence of tunnel–pile spacing on pile performance, a parametric study was conducted. The horizontal distance between the tunnel centerline and the nearest pile (on the tunnel side) was varied from 1D, 1.5D, 2D, 3D, 4D, 5D, to 6D, where D denotes the tunnel diameter (6.3 m). The corresponding results regarding pile internal forces and displacements are summarized in Table 5 and 6.

Table 5. Internal forces and displacements of pile 1 after construction of the lower tunnel

Distance (xD)	Lower tunnel						
	1	1.5	2	3	4	5	6
Mmax (kN)	22.83	21.32	20.71	21.69	23.74	24.96	25.37
Mmin (kN)	-8.442	-6.917	-5.771	-4.932	-5.442	-6.061	-6.348
Nmax (kN/m)	437.5	464.5	489.1	509.1	512.3	511.9	511.6
Nmin (kN/m)	135.2	133.9	132.7	115.5	107.5	105.2	105.3
Ux,max (mm)	5.40	5.08	4.55	3.18	1.98	1.15	0.640
Uy,max (mm)	-11.59	-8.14	-5.75	-3.04	-1.81	-1.22	-1.01

Table 6. Internal forces and displacements of pile 1 after construction of the upper tunnel

Distance (xD)	Upper tunnel						
	1	1.5	2	3	4	5	6
Mmax (kN)	15.34	15.17	17.3	21.76	24.91	25.81	25.81
Mmin (kN)	-5.456	-3.517	-3.433	-4.29	-5.572	-6.283	-6.512
Nmax (kN/m)	543.3	515.1	510.5	513.2	515	513.2	512.1
Nmin (kN/m)	146.7	149.8	144	116.8	107	104.2	105
Ux,max (mm)	9.83	8.55	7.04	4.10	2.11	1.11	0.679
Uy,max (mm)	-11.66	-8.42	-6.10	-2.98	-1.72	-1.26	-1.16

During the excavation of the lower tunnel, at a pile–tunnel spacing of 1D (6.3 m), the maximum bending moment (Mmax) decreased to 22.83 kN· compared with 25.47 kN prior to tunneling. As the spacing increased, Mmax further decreased to 20.71 kN·at 2D, before gradually increasing and reaching 25.37 kN at 6D, which is nearly identical to the initial value. This indicates that lower tunnel excavation reduces Mmax for piles located close to the tunnel (1D–2D), owing to soil movements toward the tunnel that relieve loading on the piles. Beyond 3D, the influence

of tunneling becomes negligible, with Mmax returning to values comparable to the initial condition (Fig. 6).

For the upper tunnel excavation, Mmax at 1D dropped more significantly to 15.34 kN, compared with 22.83 kN during the lower tunnel excavation and 25.47 kN before tunneling. With increasing spacing, Mmax progressively increased and reached 25.81 kN·at 5D and 6D, essentially equivalent to the pre-tunneling condition. These results confirm that the upper tunnel further amplifies soil

displacement around the piles, leading to additional reductions in M_{max} for piles located close to the tunnel ($1D-2D$). However, at larger spacings ($\geq 4D$), the effect of the upper tunnel diminishes rapidly, with M_{max} approaching its initial value.

Overall, the sequential excavation of the lower and upper tunnels produces two distinct phases of stress redistribution within the soil mass. The lower tunnel induces the first reduction in M_{max} , while the subsequent excavation of the upper tunnel imposes additional stress and displacement changes, further reducing M_{max} at piles in close proximity to the tunnel. Nonetheless, the influence decays rapidly with distance, highlighting that piles beyond approximately $3-4D$ are largely unaffected (Fig. 6).

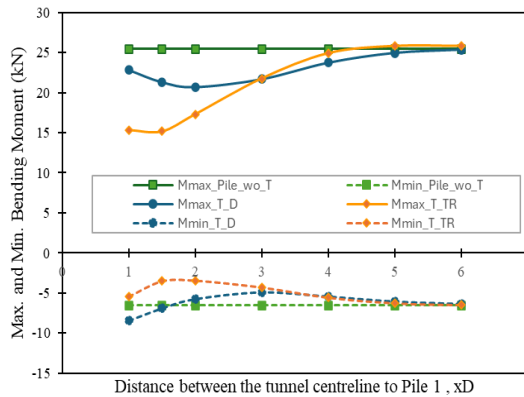


Figure 6. Max. and min. bending moments in pile 1

During the excavation of the lower tunnel, at a pile–tunnel spacing of $1D$, the maximum axial force (N_{max}) decreased significantly to 437.5 kN/m compared with 513.4 kN/m prior to tunneling. As the spacing increased, N_{max} gradually recovered, reaching 511.6 kN/m at $6D$, which is nearly identical to the initial value. This indicates that lower tunnel excavation reduces N_{max} in piles located close to the tunnel (particularly Pile 1), whereas at greater distances the influence becomes negligible and N_{max} returns to its pre-tunneling level.

In contrast, during the excavation of the upper tunnel, N_{max} at $1D$ increased to 543.3 kN/m , exceeding both the initial value (513.4 kN/m) and the value after lower tunnel

excavation (437.5 kN/m). With increasing spacing, N_{max} slightly decreased and stabilized within the range of $510-515 \text{ kN/m}$, which is essentially equivalent to the pre-tunneling condition. These results suggest that the lower tunnel, located near the pile toe, tends to induce downward drag on the pile, thereby reducing N_{max} , whereas the upper tunnel, positioned around the mid-depth of the pile, promotes additional lateral displacement and bending of the pile shaft, leading to an increase in N_{max} . The influence of the upper tunnel, however, diminishes rapidly when the tunnel–pile spacing exceeds approximately $2D$.

Regarding the minimum axial force (N_{min}), both the lower and upper tunnel excavations caused an increase in N_{min} , particularly for piles located close to the tunnel. This effect also attenuated with greater pile–tunnel distances (Fig. 7).

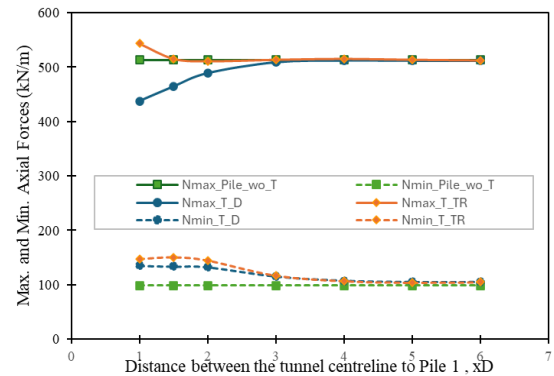


Figure 7. Max. and min. axial forces in pile 1

After the excavation of the lower tunnel, the maximum lateral displacement of pile 1 occurred at $1D$ (6.3 mm), reaching $U_{x,max} = 5.40 \text{ mm}$, the highest recorded value. This reflects notable lateral movement when the tunnel is close to the pile, primarily due to soil shifting toward the tunnel (the ground loss-induced displacement effect). With increasing distance, $U_{x,max}$ progressively decreased from 5.08 mm at $1.5D$ to 0.640 mm at $6D$, representing an 88% reduction. This indicates that the influence of the lower tunnel on pile lateral displacement diminishes rapidly with distance, consistent with the attenuation of soil disturbance.

Following the excavation of the upper tunnel, the maximum lateral displacement at 1D increased to $U_{x,max} = 9.83$ mm, representing an 82% increase compared to the lower tunnel (5.40 mm). With increasing distance, displacements reduced from 8.55 mm at 1.5D to 0.679 mm at 6D, corresponding to an approximate 93% reduction. At all distances, lateral displacement induced by the upper tunnel exceeded that of the lower tunnel, especially at piles close to the tunnel (1D–2D), reflecting stronger soil disturbance due to its shallower depth and alignment with the pile. At larger offsets ($\geq 4D$), displacements became negligible, indicating minimal tunneling influence. The tunneling sequence (lower followed by upper) was also found to have an insignificant effect on $U_{x,max}$ of pile (Fig. 8).

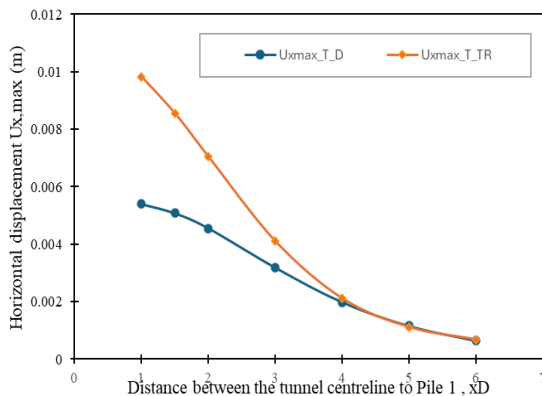


Figure 8. Max. horizontal displacement ($U_{x,max}$) of pile 1

After the construction of the lower tunnel, at 1D, the maximum vertical displacement (settlement) was, $U_{y,max} = -11.59$ mm, the largest among all distances. With increasing distance, $U_{y,max}$ decreased markedly: -8.14 mm (1.5D), -5.75 mm (2D), -3.04 mm (3D), -1.81 mm (4D), -1.22 mm (5D), and -1.01 mm (6D), representing a 91% reduction from 1D to 6D. For the upper tunnel, at 1D, the maximum settlement was $U_{y,max} = -11.66$ mm, nearly identical to that of the lower tunnel (a marginal increase of 0.6%). As the distance increased, settlement decreased from: -8.42 mm (1.5D), -6.10 mm (2D), -2.98 mm (3D), -1.72 mm (4D), -1.26 mm (5D), and -1.16 mm (6D), a 90% reduction (Fig. 9).

The largest vertical displacement occurred at the pile closest to the tunnels (1D–2D) and diminished rapidly with distance, confirming that tunneling effects on pile settlement are distance-dependent. The difference in $U_{y,max}$ between the two tunneling stages was negligible. The subsequent construction of the upper tunnel did not cause additional significant settlement but maintained the decreasing trend with distance. This suggests that soil disturbance from the upper tunnel primarily contributed to lateral displacement, while vertical settlement was governed by the lower tunnel excavation, as the soil beneath the pile toe had already stabilized after the first excavation.

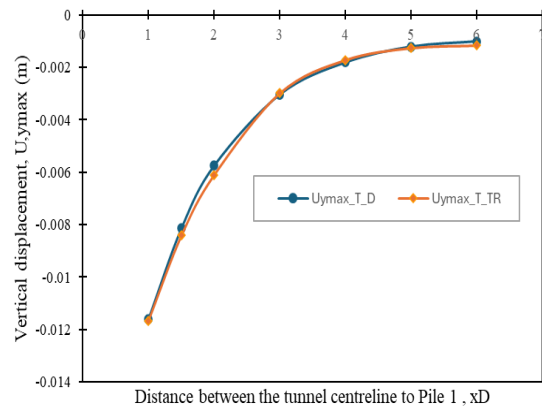


Figure 9. Max. vertical displacement ($U_{y,max}$) of pile 1

CONCLUSIONS

From the above results, it is evident that tunnel construction has a clear impact on the behavior of pile foundations. The degree of this influence depends on multiple factors. In this study, the author focused on analyzing the effect of the distance between the tunnel and the pile group. The main conclusions can be summarized as follows:

Before tunnel construction, the piles located at the outer boundaries exhibit the largest internal forces and displacements. Moving toward the center of the structure, both internal forces and displacements gradually decrease, with the central piles experiencing the smallest values.

At the same relative distance between the tunnel and the pile group (1D), the farther a pile is from the tunnel, the smaller the influence on its behavior.

Regarding the effect of tunnel position, the greater the distance between the tunnel and the pile group, the smaller the impact. When the tunnel is more than 3D away from the pile group (measured to the nearest pile on the tunnel side), the influence becomes negligible.

It should be noted that the present study was carried out using a two-dimensional (2D) numerical model, which does not fully capture Abd-Elhamed, A. (2021). Analytical Solution of Laterally Loaded Free-Head Long Piles in Elasto-Plastic Cohesive Soils. *Mathematics*, 9. <https://doi.org/https://doi.org/10.3390/math9161961>.

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the effects of the construction process (e.g., tunneling machine operation parameters, interactions between adjacent pile groups). Therefore, future work will focus on developing a three-dimensional (3D) numerical model to provide a more comprehensive simulation of the tunneling process and its impact on pile foundations.

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