Response of Existing Pile Groups Due to Twin Tunneling: A Numerical Study

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ABSTRACT

Twin shield tunneling operations frequently cross pile group foundations at close intervals in densely populated areas. The relationship between recently built tunnels and pre-existing pile foundations has been extensively studied, but the impact of various twin-parallel shield tunneling construction sequences on pile groups has seldom ever been discussed. This work investigated the complex interrelationships of soil, pile group foundations, and twin tunnel excavation. The Tunnel Boring Machine (TBM) approach and three-dimensional Finite Element Analysis (FEA) were deployed using Midas GTS-NX to assess how pile groups respond to twin tunneling construction sequences. The results indicated that at a depth of 0.3D, the corner pile experiences a 60% greater effect than the middle pile as excavation progresses from 0 to +2D before stabilizing. Furthermore, the bending moment affects the entire pile length at 0.3D, but decreases by 48% and 60% as the tunnel depth increases to 0.7D and 1D, respectively.

Keywords-twin tunnel construction; finite element analysis; pile foundations; lateral load; bending moment

I. INTRODUCTION

Many cities and countries consider tunnels an effective solution to the challenges encountered owing to congested transportation networks [1]. Constructing tunnels underground allows for the efficient use of subterranean space, making them an innovative and eco-friendly alternative. However, tunnel construction is inherently complex and hazardous compared to other construction projects. This becomes particularly problematic in soft ground conditions, where it can cause ground movement, leading to the tilting or collapse of nearby buildings [2]. Furthermore, the impact of tunneling on the ground and subsurface structures has been the subject of research, since tunnel excavation upsets the stress equilibrium of the ground [3]. Structures supported by piles exacerbate this issue [4].

There is no doubt that tunneling has advanced due to the great progress in technology, but this has not eliminated its potential problems, especially surface settlements. Uneven settlement during tunneling can lead to distortions and cracks, possibly compromising the safety of existing structures [5]. Therefore, it is important to consider how the tunnel and soil will interact while planning, designing, and constructing a new tunnel close to existing buildings [6, 7]. Recently, there has been an increasing need for double tunnels, instead of single ones, in underground transportation networks, rock formations, and soil deposits. This is due to their high structural capacity, high technological feasibility, and improved transportation efficiency [8, 9]. However, the interaction of twin tunnels with the surrounding soil is much more complex and dangerous than that of a single tunnel, which can cause damage to existing structures, regardless of whether they are supported by shallow or deep foundations. According to research on twin tunnels without adjacent structures, the excavation of a second tunnel can cause significant soil disturbance, stress elevation, stress relaxation, and expansion of the plastic soil zone [10, 11].

To understand the effects of tunneling on the adjacent pile foundations, several approaches have been carried out, which include field monitoring observations [12], as well as numerical and analytical methods [13, 14]. They have all agreed that tunnel construction affects piles and causes an increase in bending and axial force, as well as axial settlement and lateral displacement. Furthermore, the behavior of piles has been studied during different stages of tunneling, and it has been concluded that the bending moment in the lateral direction is greater than the longitudinal direction owing to the higher lateral deformation [15].

In the present study, a series of three-dimensional FEA was conducted to investigate the interaction between twin tunnels and pile groups, and to understand the effect of different construction sequences on structural behavior. Specifically, the current study aims to analyze the effects of twin tunneling on the nearby existing pile group foundation, including the bending moment, pile displacement, and pile head settlement. The main goal is to help engineers understand these interactions better so that they can lower the risks of settlement that come with TBMs during tunnel construction.

II. NUMERICAL INVESTIGATION

A. *Finite Element Model and Material Properties*

A (2 × 3) pile group, arranged with an optimal center-to-center spacing of S=3d, as proposed in [16], was modeled to examine the behavior of pile groups subjected to twin-tunnel construction. In this setup, d represents the diameter of the piles. Each pile was designed with a length (L) of 20 m and a diameter (D) of 1 m. The piles were assumed to be hinged to a pile cap, which had dimensions of 1 m thickness (tc), 6 m width (Bc), and 9 m length (Lc). Figure 1 displays the cross-sections of the pile group geometry that was used in the analysis. It also demonstrates E, the distance between the pile tip and the tunnel crown, and C, the distance between the twin tunnels' centerlines. The study involved idealized twin circular tunnels, T1 and T2, each with an external diameter (D) of 9 m and a segment thickness of 0.4 m. These tunnels were located in a clayey soil stratum, and the excavation was carried out using a TBM.

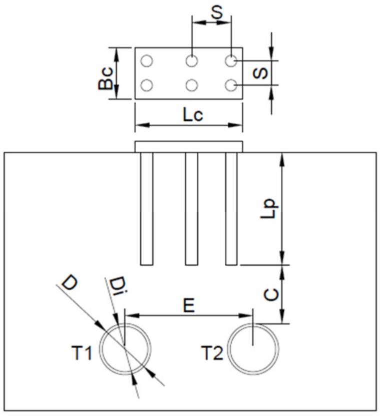


Fig. 1. The location of the twin tunnel in relation to a group of piles (not in scale).

The soil boundary modeled in this study measures 80 m in length, 100 m in width, and 60 m in height, providing sufficient dimensions to minimize boundary effects on the tunnel's behavior and soil conditions. Figure 2 illustrates the three-dimensional finite element mesh used in the numerical analysis, which was created utilizing Midas GTS-NX software. To address the concentration of high shear strains, a fine mesh was applied near the twin tunnels and pile locations, while a coarser mesh was utilized in regions farther from these zones. Additionally, the external vertical boundaries of the model were restricted from lateral movement, and the base boundary was fixed. During the twin tunnel boring process, the groundwater table was assumed to be at the ground surface, and the hydrostatic pore pressure remained constant.

Table I lists the properties of the clayey soil, as found in [17]. The Modified Mohr–Coulomb (MMC) model was used to simulate soil behavior. The tunnel excavation in shield construction is a dynamic process involving both excavation and unloading processes. In this 3D model, the soil parameters are defined using the MMC constitutive model. Unlike the standard MC model, the MMC model accounts for shear hardening. By incorporating both shear and density hardening mechanisms, it provides a more accurate representation of different soil types, from soft to hard soils, effectively capturing the unloading rebound phenomenon that occurs during tunnel shield excavation [18]. The MMC model is an elastoplastic constitutive framework that combines nonlinear elasticity with plasticity, in accordance with the plasticity theory. It takes into account the changes in elastic modulus under various loading and unloading circumstances as well as the connection between stress state and soil stiffness [19]. Additionally, tetrahedral elements were used to represent the tunnel linings, piles, pile caps, and surrounding soil. A plate element was employed to model the shield shell, and an interface element was incorporated to simulate the interaction between the pile and the surrounding soil. Table II summarizes the specific parameters used in this study.

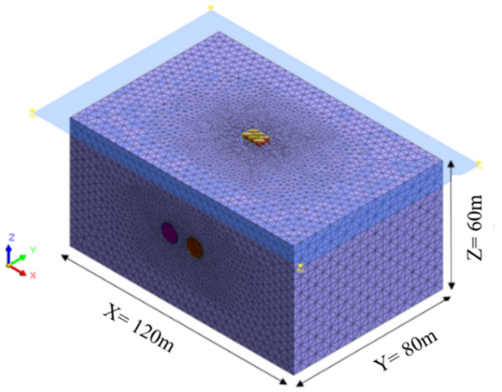


Fig. 2. The mesh and problem dimensions employed in the 3D finite element model.

TABLE I. SOIL PROPERTIES FOR NUMERICAL ANALYSIS [17]

Experimental model properties	Values
Cohesion (C), kN/m^2	10
Friction angle (φ), [°]	35
Dilatancy angle (Ψ), [°]	5
Secant stiffness in the standard drained triaxial test, E_{ref}^{50}	35000
Tangent stiffness for primary oedometer loading (E_{ref}^{oed}), kN/m^2	35000
Unloading and reloading stiffness, (E_{ref}^{ur}), kN/m^2	100000
Poisson's ratio for unloading reloading (ν_{ur})	0.2
Unsaturated unit weight (γ_{unsat}), kN/m^3	17
Saturated unit weight (γ_{sat}), kN/m^3	20

TABLE II. THE STRUCTURAL PARAMETERS OF THE CURRENT STUDY

Parameters	Elasticity modulus (E), kN/m^2	Unit weight (γ), kN/m^3	Possion's ratio (ν)
Pile	30×10^6	25	0.2
Pile cap	30×10^6	25	0.2
Tunnel lining	30×10^6	25	0.2
TBM shield	210×10^6	78.5	0.3

B. Numerical Modeling Procedure

The element birth and death technique are commonly employed in Finite Elements software, such as Midas, Abaqus, etc. This technique enables simulating the deactivation and reactivation of the materials when adding or removing them. It is particularly beneficial for analyzing scenarios, such as tunneling excavation and staged construction [20]. A series of concrete ring segments (one m in width) was connected to structure the shield tunnel linings. Two segments were added in each calculation stage. To accurately depict the shield excavation process, the model included several pressures: both shield external pressure and segment external pressure were applied along the tunnel perimeter, while jack thrust was applied at the front of the segment face and drilling pressure was delivered to the shield excavation face. A full numerical analysis was carried out following these successive steps:

- Initial stage: it includes the activation of the entire soil mass (static stress conditions with varying K_0 with depth), the tunnel excavation zone, piles, and soil layer.
- Pile activation stage: it involves substituting the soil properties of the pile regions with those of the concrete material. At this stage, pile caps are also activated.
- During the second stage, the loads are applied to the pile caps using incremental steps. To isolate the effects of shield tunneling on the pile cap behavior, the displacements from the initial and first stages are reset to zero.
- The third stage begins by simulating the tunnel advancement. The excavation of the first ring is performed, and it is replaced with the shield every 2 m. Drilling pressure and shield external pressure are applied.
- Tunnel Advancement (Stages 4 to 6): The shield advancement continues, the drilling pressure and shield external pressure are applied, the first ring of segments is installed within the shield, and the jacking force is applied to be secured.
- Segment installation (Stages 7 to 10): Four rings are installed behind the shield and external pressure is applied on the segments.
- Grouting and Material Hardening (Stage 11): The next ring is installed and the grout hardens by modifying its material properties.
- Completion of Excavation (Stages 12 to 49): Stages 3-7 are repeated, continuing the excavation process and ring installation until all tunnel segments are completed.

C. *Validation of the Numerical Model*

The El-Azhar Road tunnels are analyzed by comparing the numerical results generated using Midas GTS-NX with field measurement data to compute the surface settlement. The twin tunnels were constructed using a TBM with a diameter of 9.56 m, while the liner diameter of the tunnels is 9.06 m [21]. The tunnels are located 20 m below the ground surface, with a horizontal spacing of 13.5 m between the north and south tunnels. In [21], the geotechnical properties of the soil layers are provided. The accuracy of the numerical model is assessed through this comparison, which reveals a strong correlation between the computed and measured results, as portrayed in Figure 3.

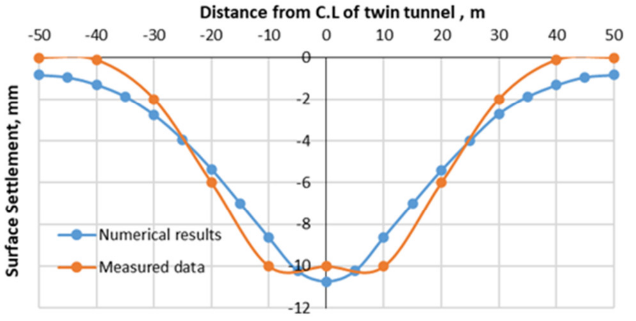


Fig. 3. Comparisons between computed and measured ground surface settlements caused by the construction of the El-Azhar Road tunnels.

D. *Parametric Study*

The main goal of this study is to investigate how the clearance depth between the tunnel crown and the pile tip and the center-to-center spacing of the twin tunnels affect the behavior of the pile group at different stages of the tunnel progress, namely at -4D, -2D, 0D, +2D, and +4D from the center of the twin tunnels in the longitudinal direction. The considered construction sequences include different scenarios, where both tunnels, T1 and T2, are constructed simultaneously. In this study, the clearance depths (C) were set at 0.3D, 0.7D, and 1D, while the center-to-center distances between the twin tunnels were chosen as E = 1.5D, 2D, and 3D, with D representing the outer diameter of the tunnel. Figure 4 illustrates the parametric studies conducted in this research.

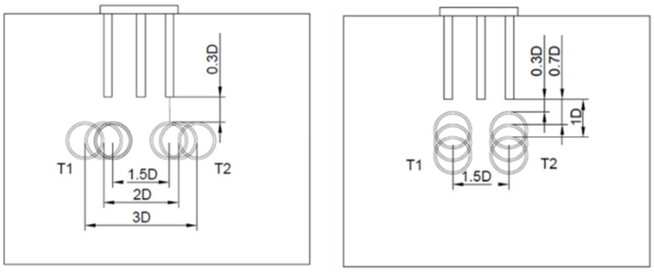


Fig. 4. Twin tunnel construction schematic with different geometric parameters.

III. RESULTS AND DISCUSSION

A pile group consisting of 2 x 3 piles, as shown in Figure 1, was subjected to vertical loads and twin tunnel excavation. According to the analysis, the twin tunnel construction had an identical effect on the corner piles' axial displacement, lateral deflection, bending moment, and axial force because of their comparable surrounding conditions. The middle piles are no exception. As a result, the main goal of the current study is to examine how the one-center and one-corner piles behave inside the pile group. Figure 5 shows the comparison between all the corner and middle piles based on the results from Midas GTS-NX. The results have been extracted at the end of the tunnel construction, with a distance between the center of the tunnels 1.5D and depth (C)= 0.3D.

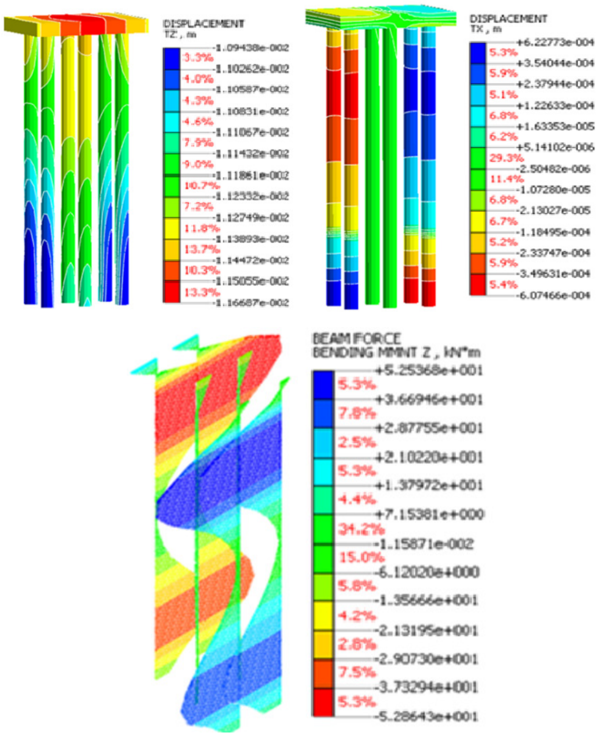
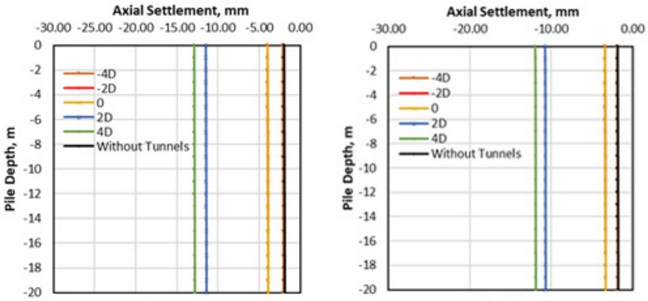


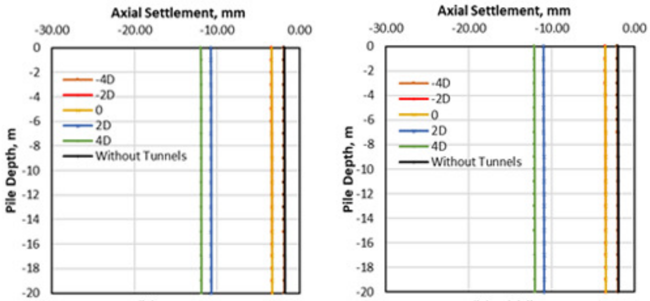
Fig. 5. Numerical simulation results of all piles in a group after twin tunnel constructions: (a) axial settlement, (b) lateral displacement, and (c) bending moment.

A. *Effect of Twin Tunnels on the Axial Settlement of Pile Group:*

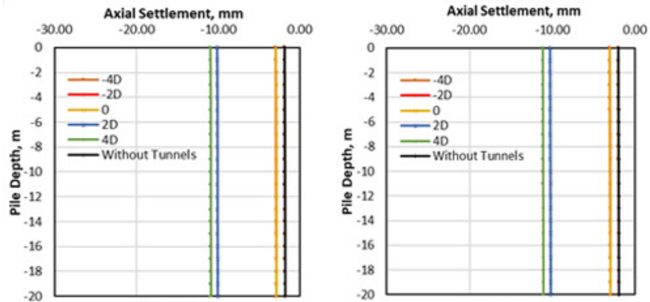
Figure 6 presents the uniform axial settlement distribution of the middle and corner piles in a group subjected to varying twin tunnel excavation progress. The tunnels were constructed at different depths: 0.3D, 0.7D, and 1D, from the pile tip to the tunnel crown, with the center-to-center distance between the tunnels fixed at 1.5D. In Figure 6, it is observed that for the corner piles, the tunnel excavation effect begins when the tunnel face reaches the center of the pile cap due to stress redistribution. The excavation impact intensifies, reaching a 72% increase at +2D, before gradually declining by 8% as the excavation advances, eventually stabilizing. Additionally, for deeper tunnels, the stress distribution becomes more spread out, and the pile tips may not experience significant direct impact unless they extend to the tunnel depth. However, piles that reach or exceed the tunnel level may still undergo settlement, especially in soft soils, where tunneling disturbs the underlying strata. Similarly, the axial settlement of middle piles increases by about 75% when the excavation reaches +2D, and this increase becomes smaller and stabilizes after +4D. This is because the middle pile is affected not only by the twin tunnel effects, but also by the interaction with the surrounding piles in the group.



(a) corner (a) middle



(b) corner (b) middle



(c) corner (c) middle

Fig. 6. Axial settlement with depth for corner and middle piles at different construction stages, with 1.5D distance and (a) 0.3D, (b) 0.7D, and (c) 1D depth.

In addition, Figures 7(a), 7(b), and 7(c) demonstrate how the spacing between the twin tunnels affects the pile group behavior. The results indicate that the axial settlement rises as the tunnel spacing decreases. This causes the stress and deformation zones of the twin tunnels to overlap significantly, increasing ground settlement and resulting in more pronounced interactions with the nearby pile foundations. The piles positioned between the tunnels are particularly susceptible due to the combined effects of ground loss and stress redistribution from both tunnels.

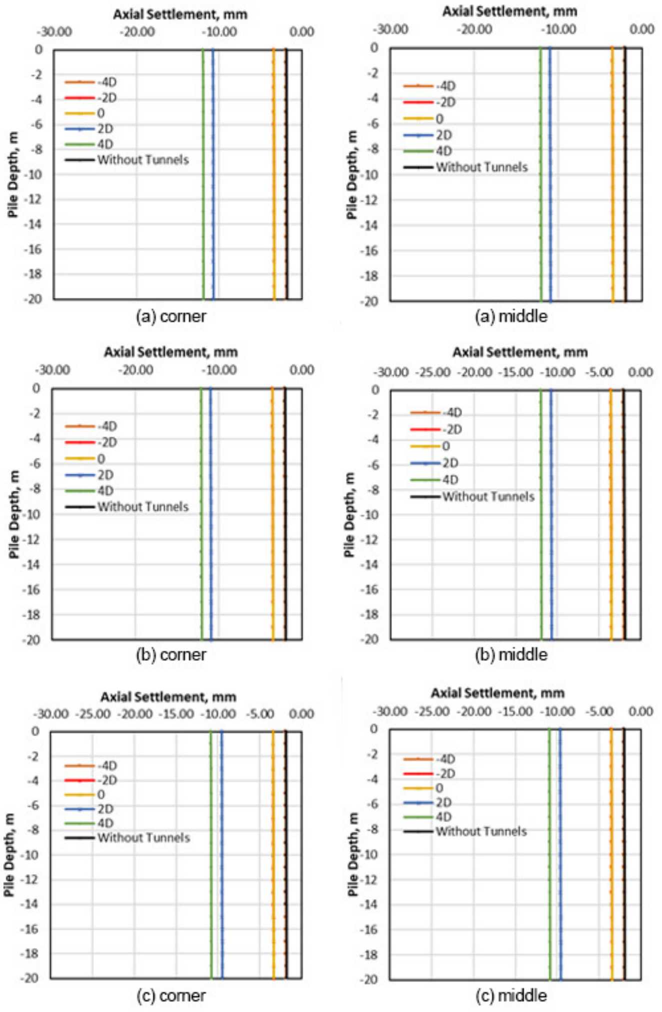


Fig. 7. Axial settlement with depth for corner and middle piles at different construction stages, with 0.7D depth and at (a) 1.5D, (b) 2D, and (c) 3D distance.

B. *Influence of Twin Tunnels on the Lateral Displacement of the Pile Group:*

Figure 8 presents the lateral displacement values for varying pile depths under the influence of twin tunnel excavation at different stages: -4D, -2D, 0, +2D, +4D, and in the absence of tunneling. It can be observed that no significant impact is noted as the excavation progresses from -4D to 0, relative to the tunnel center. However, the lateral displacement of the corner pile increases by about 74% as the excavation advances from 0 to +2D from the tunnel center. For the middle pile, the pattern of lateral displacement differs along its length due to the confining pressure from the adjacent piles in the group, in addition to the influence of tunnel excavation. Furthermore, the effect of the twin tunnel excavation diminishes as the excavation depth increases vertically from 0.3D to 1D.

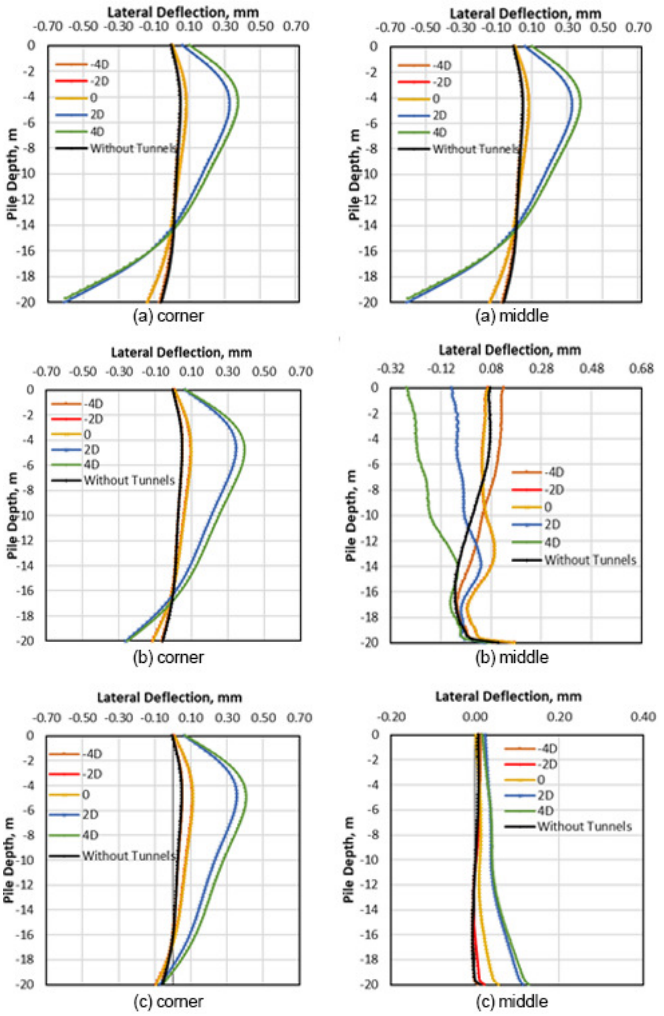
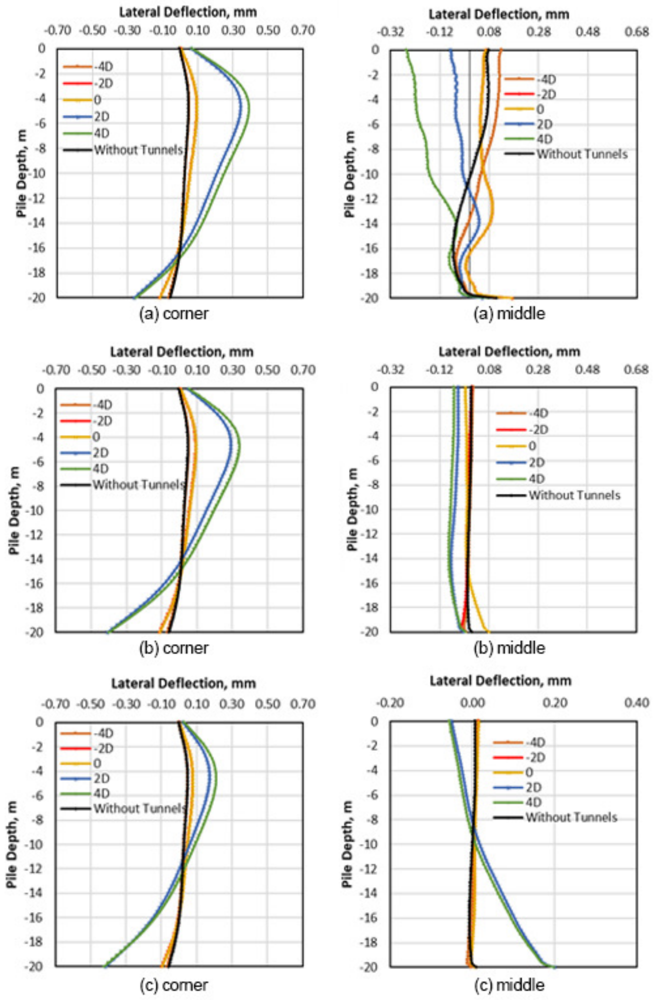


Fig. 8. Lateral displacement with depth for corner and middle piles at different construction stages, with 1.5D distance and (a) 0.3D, (b) 0.7D, and (c) 1D depth.

Figures 9(a), 9(b), and 9(c) depict the lateral displacement of piles subjected to twin tunnel excavation at a fixed depth of 0.7D, with varying horizontal twin tunnel distances of 1.5D, 2D, and 3D. The findings indicate that as the spacing between the twin tunnels decreases, the excavation has a lesser impact on the lateral displacement of the pile group compared to wider spacing. This behavior occurs because the confined soil between the twin tunnels provides resistance to lateral displacement, thereby reducing the excavation's influence on the piles.



(a) corner (a) middle

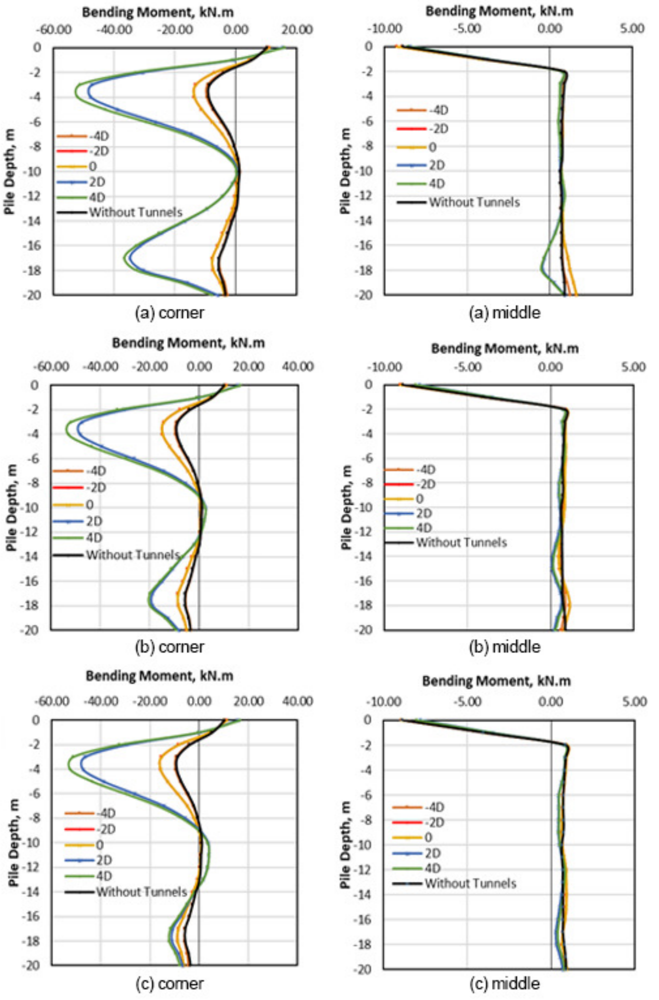
(b) corner (b) middle

(c) corner (c) middle

Fig. 9. Lateral displacement with depth for corner and middle piles at different construction stages, with 0.7D depth and at (a) 1.5D, (b) 2D, and (c) 3D distance.

C. *Twin Tunnel effects on the Bending Moment of the Pile Group:*

Figures 10(a), 10(b), and 10(c) display the distribution of the bending moments with depth for corner and middle piles under axial force, and the effects of the twin tunnel construction at three different depths: 0.3D, 0.7D, and 1D, with the distance between the twin tunnels set at 1.5D. At a depth of 0.3D, as evidenced in Figure 10(a), the results show that the corner pile experiences a greater effect than the middle pile, with the effect increasing by approximately 60% as the tunnel excavation progresses from 0 to +2D and then stabilizing after +2D. Comparing Figures 10(a), 10(b), and 10(c), it is noted that the bending moment increases along the entire length of the corner pile when the tunnel depth is 0.3D. Specifically, the affected length diminishes by 48% at 0.7D and 60% at 1D, indicating a notable decline in the impact as the tunnel is positioned deeper. In contrast, for the middle pile, only the last quarter of the pile is affected by the twin tunnel construction at an excavation depth of +4D, and the effects diminish when the tunnel depth reaches 0.7D.



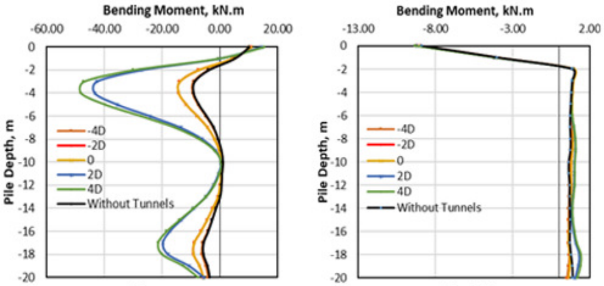
(a) corner (a) middle

(b) corner (b) middle

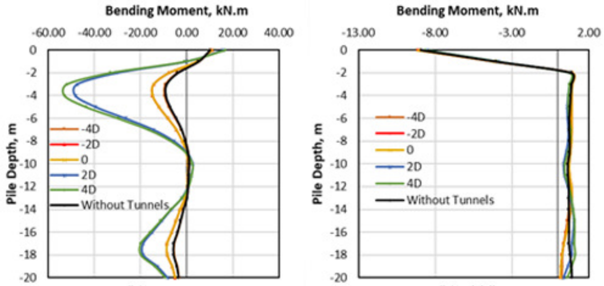
(c) corner (c) middle

Fig. 10. Bending moment with depth for corner and middle piles at different construction stages, with 1.5D distance and (a) 0.3D, (b) 0.7D, and (c) 1D depth.

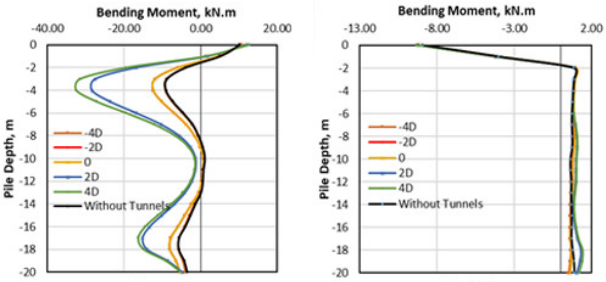
Figure 11 illustrates the bending moment relationship for both piles at different pile depths, due to twin tunnel excavation under the pile group, with the distances between the twin tunnels varying from 1.5D to 2D and 3D. The results reveal that at the initial stage of tunnel construction, the corner pile experiences no bending moment. However, as the tunnel advances, the bending moment gradually increases. A significant rise in bending moment occurs when the tunnel face reaches the center of the pile cap, followed by a further increase as the tunnel moves beyond the pile cap at distances of 2D and 4D. Eventually, the increase in bending moment becomes negligible. The bending moments of the piles decrease as the spacing between the twin tunnels increases, with reductions of 10% and 25% for tunnel excavation depths of +2D or greater, as the spacing increases from 1.5D to 2D and 3D, respectively. No further changes in bending moments are observed after +2D excavation. Additionally, the middle pile is less affected than the corner pile due to the interactions between the piles.



(a) corner (a) middle



(b) corner (b) middle



(c) corner (c) middle

Fig. 11. Bending moment with depth for corner and middle piles at different construction stages, with 0.7D depth and at (a) 1.5D, (b) 2D, and (c) 3D distance.

IV. CONCLUSION

A set of 3D finite element calculations deploying the Modified Mohr–Coulomb (MMC) constitutive model and Midas GTS-NX software were used to investigate how pile group foundations behave during the construction of a twin tunnel. Axial settlement, lateral displacement, and bending moment were among the crucial elements that were examined in this study, which concentrated on pile responses at different excavation phases. Additionally, the study evaluated several variables that affect pile behavior, such as the vertical distance between the pile top and the tunnel crown and the center-to-center distance between the twin tunnels. The main conclusions drawn are:

- Axial settlement increases for both the corner and middle piles as the twin tunnel excavation progresses, with deeper tunnels causing a more distributed effect. Reduced spacing between tunnels leads to higher axial settlement due to overlapping stress and deformation zones.
- The lateral displacement values for piles under twin tunnel excavation show no significant impact as the excavation progresses from -4D to 0, relative to the tunnel center. However, the lateral displacement of the corner pile increases by about 74% as the excavation advances from 0 to +2D. For the middle pile, the lateral displacement varies along its length due to the confining pressure from adjacent piles in addition to the tunnel excavation effects.
- As the excavation depth increases from 0.3D to 1D, the tunnel excavation impact diminishes. Moreover, when the horizontal distance between twin tunnels decreases, the excavation has a lesser effect on the lateral displacement due to the resistance provided by the confined soil between the tunnels.
- The bending moments increase for the corner piles with tunnel excavation, peaking at +2D and stabilizing thereafter, while the effect on middle piles is more localized. As tunnel spacing increases, the bending moments decrease, with the middle pile being less affected due to pile interactions.

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