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# Investigation on Existing Tunnel Response to Piles Construction: A Numerical Study

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**Abstract**

Deep foundations are frequently built close to existing tunnels in the urban environment. Tunnels can only withstand very small movements. The construction of bored piles and/or the subsequent loading of the piles may result in unbearable movements or stresses that could result in cracking of the tunnel linings, which worries obstacles to the tunnel structure. This research presents an understanding of the interaction issue and investigates and evaluates various geometric factors that determine the effect of the construction of the pile on the existing tunnel. However, numerical modeling was established utilizing a modified Mohr-Coulomb constitutive model for the soil strata. Numerous factors have been examined, including different locations of the pile tip to the tunnel centerline as well as variable pile diameters and lengths. The numerical analysis results revealed that the bending moment decreases as the distance from the tunnel increases from 8 to 12 m and then remains constant, while the shear stress is not affected considerably. In addition, the shear stress and bending moment increase with pile diameter and length due to the increased confinement caused by the pile. The spacing has a considerable effect on the horizontal displacement with very little effect on the vertical displacement. Moreover, there is an increase in the shear force developed in the tunnel lining with pile diameter for different spacings between the tunnel and pile. This increase becomes smaller as the pile length increases. At small spacing between the pile and tunnel (8.3 m and 12.5 m), the bending moment in the tunnel lining decreases as the pile length increases.

*Keywords:* Tunneling; Piles; Construction; Deformation; Shear Force.

## 1. Introduction

All over the world, numerous subway tunnels have been constructed in major cities because of the rapid development of underground metro systems, which are the backbone of urban transportation. These tunnels also need a lot of work to ensure their safety and functionality due to the growth in usage and to supplement the high-rise buildings in the urban regions. The interaction and impacts between the soil-tunnel pile in the urban region must be considered because there is a major effect of pile construction on the nearby tunnels [1–4].

It is widely accepted that changes to the surrounding environment in major cities, such as deep excavation, pile installation, dewatering, and tunneling, have an impact on metro tunnels in a variety of ways. Due to the increase in imbalanced lateral pressures of soil, the lateral soil displacement caused by the installation of the pile frequently causes

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further deflection in nearby existing tunnels. Such displacement or deformation may cause the lining joints to open, the bolt stress to rise, and the internal force in tunnels to be redistributed, all of which have a severe negative impact on the bearing capacity and tunnel service function. Therefore, it is imperative to assess the potential impact of pile installation on the integrity and stability of the existing tunnels [5–7].

It is worth mentioning that the issue of pile-tunnel interaction can be divided into two categories according to the sequences of construction in which piles and tunnels were built: the impact of tunneling on piles [8–11] and the impact of pile construction on tunnels [12, 13]. However, this interaction leads to two basic types of interaction difficulties, both of which are complicated. Because of the inevitable variations in stress and deformation brought on by tunnel traffic, piles of structure may eventually become unserviceable. Therefore, tunneling has an impact on neighboring pile foundations. Inevitably, bored piles change the stress and deformation in the ground, which could ultimately affect the serviceability of a nearby tunnel. Therefore, the pile foundations have an impact on the nearby tunnel [14–16].

Meanwhile, Yin et al. (2023) [17] studied the effects of the excavation foundation pit on tunnels. It was found that the resulting distortion in the underlying tunnel gradually decreases as the tunnel depth and the foundation soil stiffness both rise. On the other hand, an increase in the dimensions of the foundation pit excavation (length and width) causes the underlying tunnel to gradually distort. Moreover, Mahajan et al. (2023) [18] conducted experimental work to study the impact of pile loading on the tunnel in Delhi silt. To examine the effect of pile loading near the existing tunnel, a small-scale testing facility was established. The results demonstrated that different pile loading stages significantly affect the strain in the tunnel lining when a row of piles is located within 12 times the pile diameter from the tunnel axis.

Jeon et al. (2020) [19] examined the interaction between a shielded TBM tunnel and a single pile using 3D finite element numerical analysis when the tunnel goes through the bottom part of a single pile with reinforcement conditions between the pile foundations and the tunnel. The results indicated that the relative positions of the tunnel and the pile had a significant impact on the behavior of the pile. In addition, the single pile with the highest level of ground reinforcement had a 30% lower maximum axial force than the pile without reinforcement. Additionally, Yao et al. (2008) [12] carried out centrifuge tests to monitor the pile loading-induced deformation of an existing tunnel liner. They found reduced distortion at increasing pile-tunnel separation distances. In addition, they discovered that a longer pile had a significant impact on the lining, regardless of tunnel size or excavation depth.

On the other hand, Yoo (2014) [20] has conducted a 3D finite element model to investigate and comprehend the impact of the pile-supported bridge construction on an already-existing tunnel. When the distance between the pile tip and the tunnel lining reaches 1.0D and 0.5D, respectively (D is the pile diameter), the results showed that the influence of pile-supported bridges on the tunnel is minimal for both centrally and eccentrically loaded tunnels. Furthermore, Lueprasert et al. (2017) [21] constructed 3D elastoplastic numerical analyses to assess load piling near an existing tunnel with varied positions of the pile tip and its impact on the tunnel and soil strata. It had been suggested that a certain technique for tunnel deformation be used. In addition, the shape of the deformation of the tunnel is a rotating ellipse or kidney shape in the case of the pile tip below or above the tunnel lining, as clearly explained by Lueprasert et al. (2023) [22].

Zheng et al. (2017) [23] used the finite element method to determine the tunnel deformation characteristics brought on by excavations. The results show that the diaphragm wall can successfully reduce tunnel distortion. The excavation of the foundation pit will cause compression on the upper surface and tension on the lower surface of the adjacent tunnel, and the stress redistribution is quite intricate.

At the same time, Zhuang et al. (2023) [24] conducted a 3D finite element analysis to investigate the response of adjacent tunnels to excavation-related deformation under different scenarios. The results indicated that the excavation width and depth, the distance between the top of the tunnel and the bottom of the foundation pit, and the distance between the foundation pit and the tunnel centerline have a significant impact on the adjacent tunnel displacement. In addition, Lim et al. (2023) [25] investigated the tunnel pile interaction, considering a parametric study of various sequences of construction between pile and tunnel depending on finite element analysis using ABAQUS software. These parametric studies involve sequences of pile-tunnel and tunnel-pile. They found that in the case of the sequence of tunnel piles, there is no significant influence on the tunnel due to the little stiffness imposed by the single pile model. In addition, even after installing piles, a mirror effect was seen on both sides of the tunnel.

However, as it is clearly evident in this review, a complicated problem of the construction of deep foundations, such as bored piles above and near the tunnels, has not been addressed in the literature. Thus, the primary aim of this research is to understand the interaction issue and to investigate and evaluate a series of parametric studies that illustrate the influence of the pile construction on the existing tunnel. To address this gap in the state of the art, a 3D finite element model has been established to address the research objective. In addition, the study flowchart is shown in Figure 1.

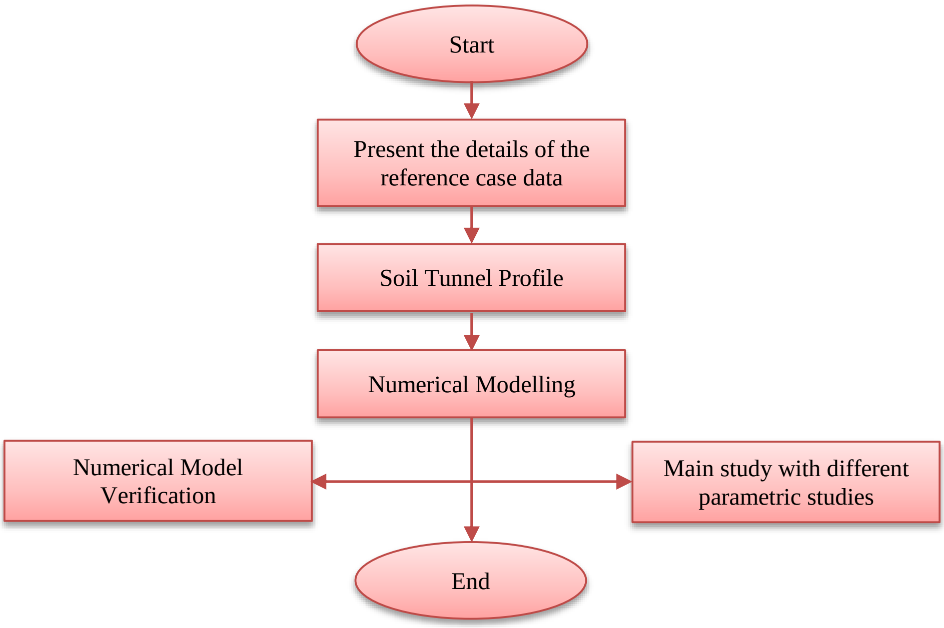



**Figure 1. Present study Flowchart**

## 2. References Case

The reference case study of the Heinenoord tunnel project in the Netherlands is idealized in the analysis to assess the proposed 3D finite element modeling of soil-structure interaction. The tunnel is circular, with an outer diameter of 8.3m and a lining thickness of 0.35 m. This tunnel is excavated in a sand layer of typical North Bank subsoil, and the distance between the crown of the tunnel and the ground is 11.35 m. In addition, the tunnel was executed using a slurry shield.

Figure 2 presents the tunnel location relative to the soil layers. The soil layer properties are adopted from the study by Möller & Vermeer (2008) [26]. In addition, the soil stratification started with a filling with a depth of about 4m, followed by about 19.25 m-thick sand. The last layer consists of clay, with a local part of sand extended to the end of the bore. The groundwater table was encountered at a distance from the surface of the ground of around 1.5 m.

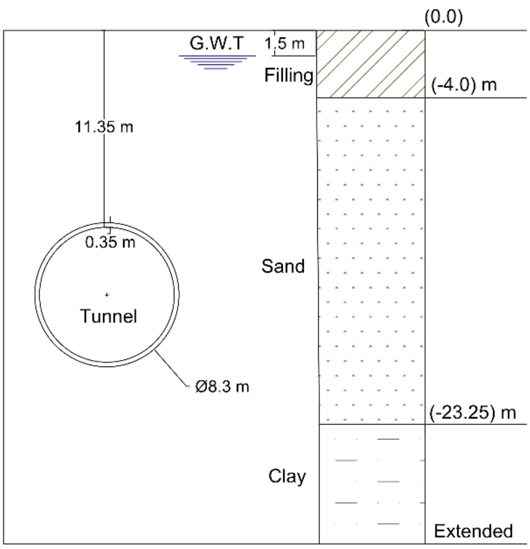



**Figure 2. Soil profile of Heinenoord shield tunnel**

### 2.1. Finite Element Mesh and Boundary Conditions

A 3D model is constructed to validate the numerical simulation of the tunnel construction of the Heinenoord shield tunnel using the Midas GTS-NX finite element package. The dimensions of the mesh were 8.7D, 9.6D, and 6D in the longitudinal, width, and vertical directions, respectively. In the numerical model, these dimensions are sufficient to reduce boundary effects due to the massive increase in mesh size, which has no impact on the analysis results [27, 28]. In this research, the 3D numerical model is displayed in Figure 3. The mesh used in the numerical model consists of 13,517 nodes and 74,823 elements. In addition, the boundary conditions are fixed and free on the bottom and top surfaces, respectively. While the four side surfaces are unrestrained in the vertical direction only.

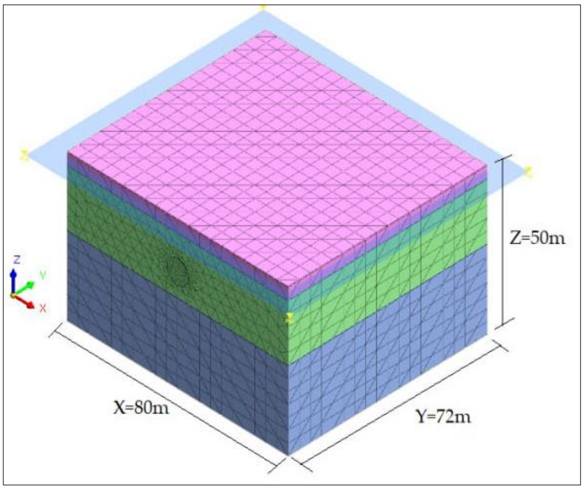



**Figure 3. 3D finite element model**

## 2.2. Constitutive Model and Model Parameters

In this study, based on Möller and Vermeer (2008) [26], the constitutive model of soil strata was simulated as a Modified Mohr-Coulomb (MMC) model, also known as the Hardening Soil Model. It is worth mentioning that the tunnel is an unloading process and a dynamic excavation in the construction of the shield [27, 29]. In contrast to the Mohr-Coulomb constitutive model, the MMC constitutive model may account for shear hardening. To more accurately depict the unloading rebound phenomenon during the shield construction, the impacts of the shear and density hardening processes can better imitate the features of different types of soil, including soft and hard soil [30]. In addition, three additional soil stiffness characteristics are also taken into account by the MMC constitutive model: triaxial loading stiffness, oedometer loading modulus, and unloading-reloading modulus. $E_{oed}$ and $E_{50}$ typically take on the same value, while $E_{ur}$ typically takes on a value that is three times that of $E_{50}$ [31]. The physical properties of the soil layers are presented in Table 1.

**Table 1. Engineering properties of the soil layers**

| Parameter \ Soil Layers | Filling | Sand | clay |
|---|---|---|---|
| Thick. (m) | 4 | 19.25 | 26.75 |
| Unit weight (kN/m$^3$) | 16.5 | 20 | 20 |
| Friction angle (0) | 27 | 35 | 31 |
| Cohesion (kPa) | 3 | 0 | 7 |
| Lateral earth pressure coefficient (-) | 0.58 | 0.47 | 0.55 |
| Poisson's ratio (-) | 0.34 | 0.30 | 0.32 |
| Triaxial loading stiffness $E_{50}$ (MPa) | 14 | 35 | 12 |
| Oedometer loading stiffness $E_{oed}$ (MPa) | 14 | 35 | 7 |
| Triaxial unloading stiffness $E_{ur}$ (MPa) | 42 | 105 | 36 |

On the other hand, the tunnel lining and shield machine were simulated using a linear elastic model. Additionally, the segments use solid elements, while the grouting and shield shell use two-dimensional plate elements. Table 2 contains the structural properties that were used in the numerical analysis.

**Table 2. Structural parameters adopted in the numerical model**

| Parameters | Pile | Lining | Shield | Grouting |
|---|---|---|---|---|
| Elasticity modulus (MPa) | $3.45\times10^4$ | $3\times10^4$ | $2\times10^4$ | $1\times10^4$ |
| Unit weight (kN/m$^3$) | 25 | 24 | 78 | 20 |
| Possion's ratio (-) | 0.15 | 0.15 | 0.3 | 0.2 |

## 2.3. Numerical Modeling Procedure

The same materials as the soil layers and structural elements outlined in the preceding section were used to create three-dimensional models. Shield tunnel lining is constructed from a series of concrete ring segments, each measuring around 1m in length (two segments of 1m are constructed in one calculating stage). The numerical modeling was analyzed on the 44 stages including the initial stage. The modeling stages as follows:

- Simulate initial soil stresses.
- Stages 1 to 7: shield progress, the face pressure load is activated, excavation of the first segment of the lining, and replaced it with the shield every 2 m.
- Stage 8 to 10: Setting up 3 rings behind the shield and the grout pressure is applied simulating the soft grout behind the tail skin of the shield.
- Stage 11: erecting the next ring and the soft grout is considered hardened.
- Stage 12 to 44: repeating stages from 1 to 11.

### 2.4. Verification of the Numerical Model

For numerical model validation, a comparison between in-situ measurements and numerical results has been conducted. Figure 4. shows the comparison between them, and it can be noted that there is a good agreement between the measurements.

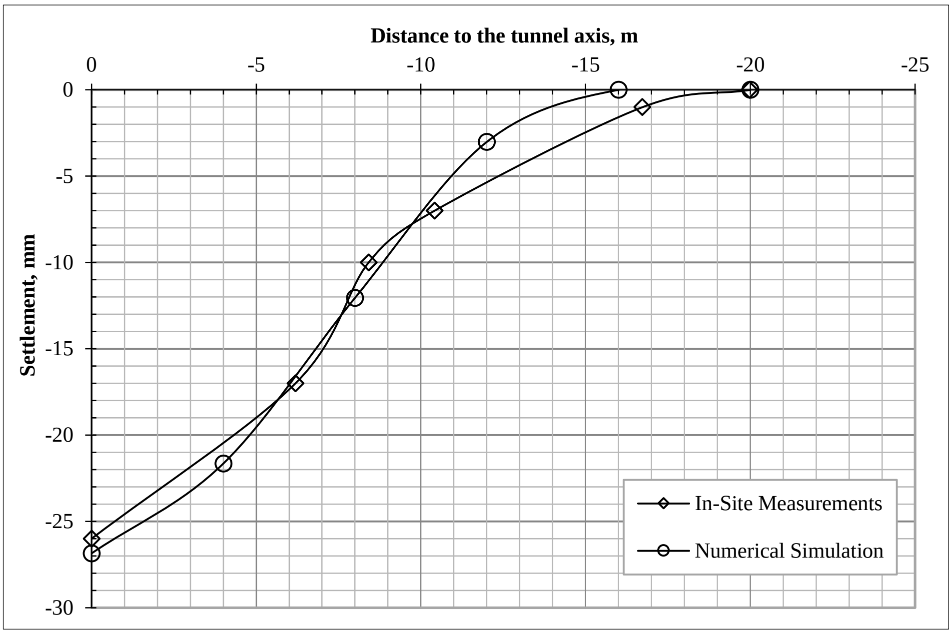



**Figure 4. Transverse settlement trough of Heinenoord tunnel**

## 3. Main Study

After verification, the finite element approach using Midas GTS-Nx can be used to resolve the interaction issue of the influence of the pile construction on an existing tunnel lining. There are two steps for modeling using finite element analysis. The first stage presents the excavation of the tunnel, which is built before the piling foundations. The same construction sequence as explained in Section (2.3) which consists of deactivated soil elements in the excavated zone while lining elements are excavated. The second phase entails the single pile installation that is close to the tunnel.

The displacements and internal forces that develop in the lining during the pile's excavation are used to evaluate the effect of the bored pile construction on a nearby tunnel. Numerous numerical analyses of the tunnel lining with a single nearby pile present have been done. The location of the pile tip in relation to the tunnel centerline, the diameter, and the length of the pile are three factors that are the parametric analysis in this work. In this research, all the parameters (soil layers, lining, pile properties, water level, boundary conditions, and constitutive models), as described for the validation model have been used.

### 3.1. Effect of the Pile Position Relative to the Tunnel

Figure 5 shows the distribution of both the vertical and horizontal displacements of a node at the tunnel crown for different distances between the bored pile and the tunnel. It can be seen that the vertical displacement is always larger than horizontal displacement. This may be due to the vertical overburden pressure. Also, the pile length and diameter seem to have no effect on both the horizontal and vertical displacements.

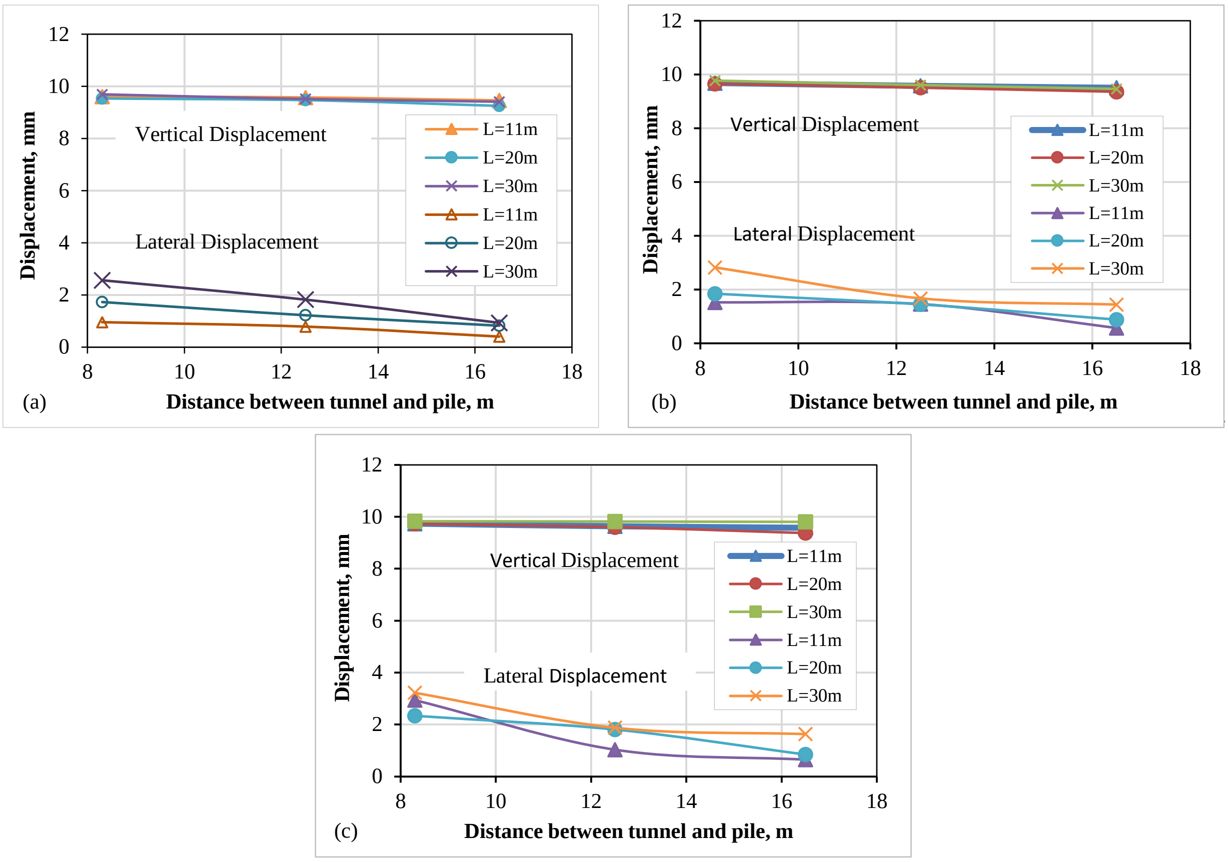



**Figure 5. The relationship between the vertical and lateral displacement and the distance between tunnel and pile (S) at different pile lengths (L= 11, 20, and 30) m with different pile diameters a) D= 60 cm, b) D = 80 cm, and c) D =100 cm**

Figures 6 and 7 present the variation of both the maximum shear stress and bending moment in the tunnel lining for different distances between the tunnel and pile. It is noticed that the bending moment decreases as the distance from the tunnel increases from 8 to 12 m then remains constant, while the shear stress is not affected considerably. The shear stress and bending moment increase with pile diameter and length due to increased confinement caused by the pile.

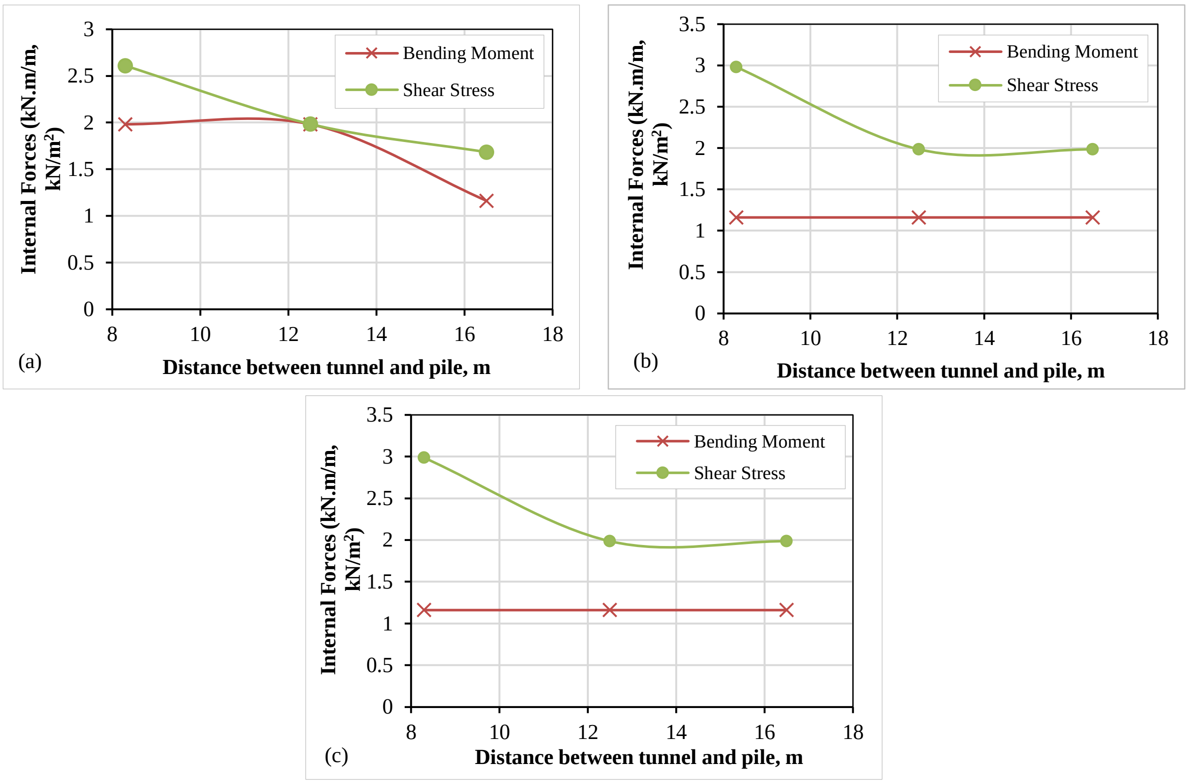



**Figure 6. Bending moment and shear stress in the tunnel lining relative to the distance between tunnel and pile with pile diameter a) D = 60 cm, b) D = 80 cm, and c) D=100 cm with constant pile length (L=11 m)**

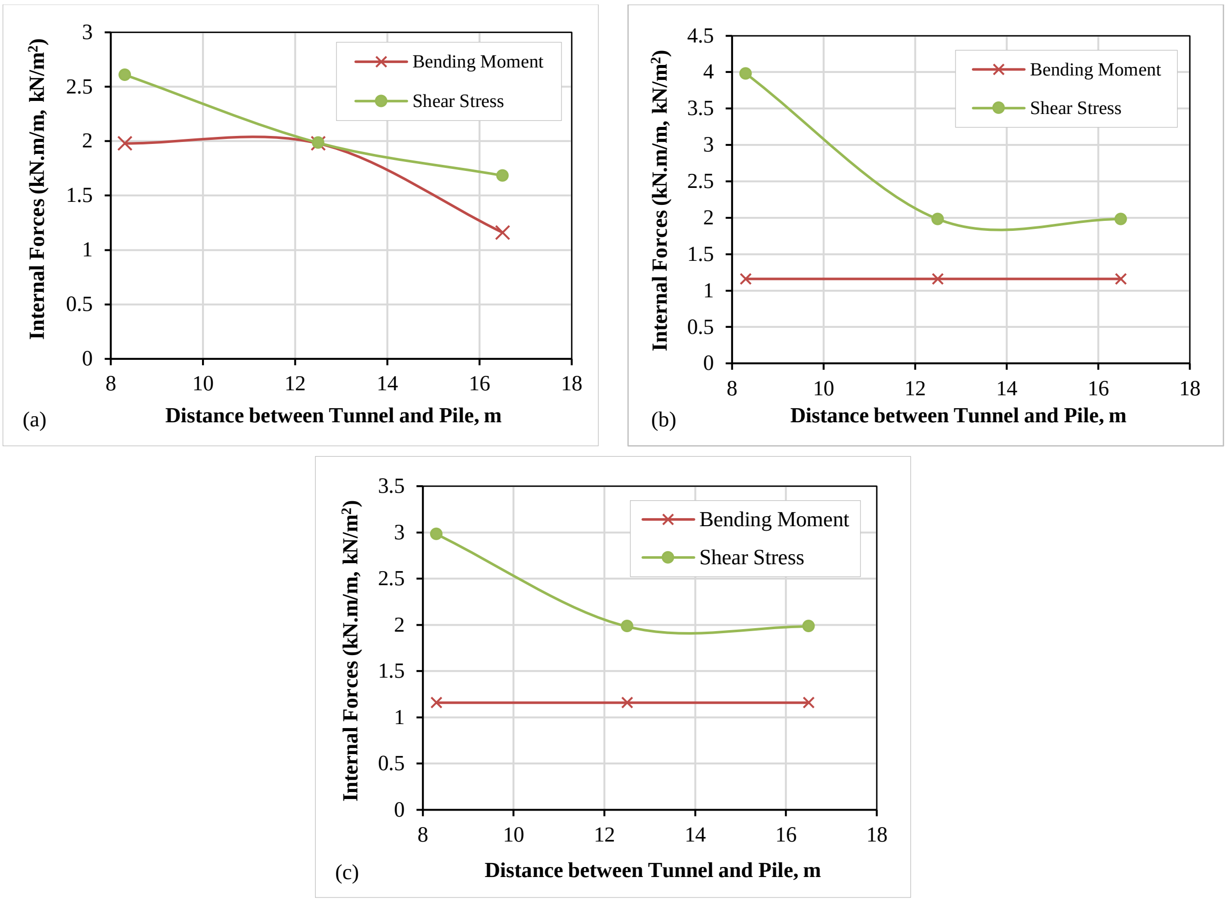
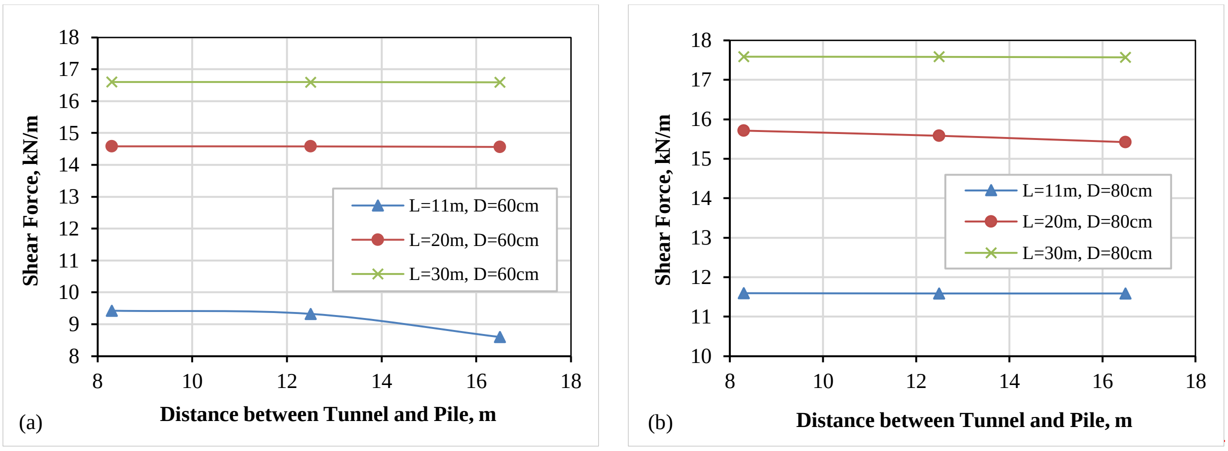



**Figure 7. Bending moment and shear stress in the tunnel lining relative to the distance between tunnel and pile with pile length a) L=11 m, b) L= 20 m, and c) L= 30 m with constant pile diameter (D = 60cm)**

Fattah et al. (2013) [32] conducted that the settlement trough of soil owing to tunnel construction is generated by stress relief and subsidence due to support movement by excavation. In addition, as the tunnels depth decreases, the maximum horizontal movement shifts away from the tunnels center.

However, the tunnel deformation may be impacted by the way the foundation (pile) pit was dug out. The primary cause of the tunnel distortion is the soil directly above it. In addition, the surrounding soil stress condition will change as a result of the foundation pit excavation, primarily due to the additional tension created by the unloading of the original soil inside the foundation pit. The nearby existing tunnel will deform via settling, bulging, bending, and twisting because of the increased forces brought on by the unloading. In extreme circumstances, the tunnel structure may be harmed, fractured, out of alignment, and/or have joint leakage, which will impair the physical operation of the existing tunnel.

Figure 8 shows the variation of the maximum shear stress in the tunnel lining with distance between the tunnel and bored pile for different pile lengths and diameters. The figure depicts the larger effect of pile length in increasing the shear stress while there has been a small effect of the pile diameter.



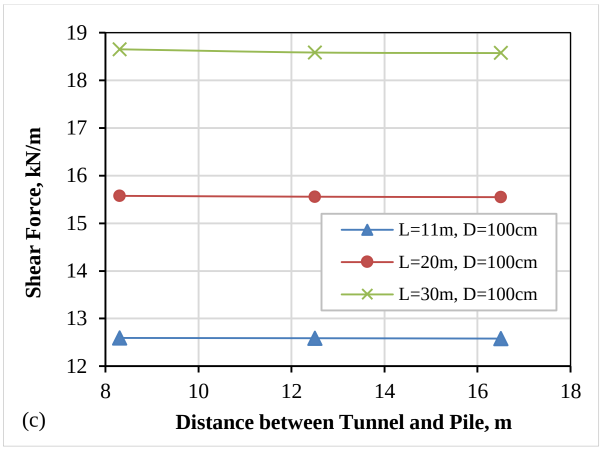



**Figure 8. Shear force in the tunnel lining relative to the distance between tunnel and pile with different pile length (L=11, 20, and 30) m and pile diameter equal to a) 60 cm, b) 80 cm, and c) 100 cm**

## 3.2. Influence of Pile Diameter

Figure 9 shows the effect of diameter of piles constructed at different spacings from the tunnel on the vertical and horizontal displacements. It is important to conclude that the spacing has a considerable effect on the horizontal displacement with very little effect on the vertical displacement.

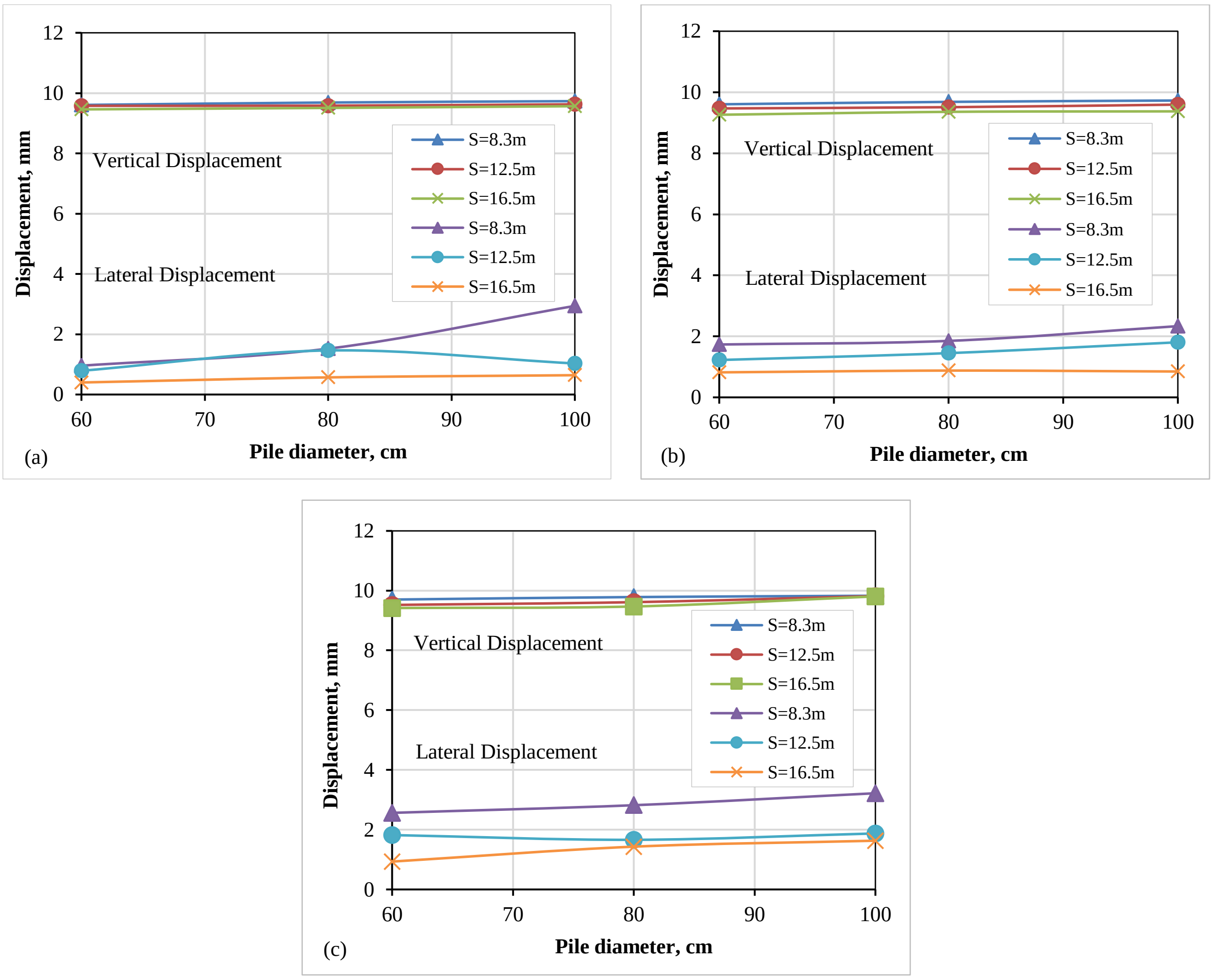



**Figure 9. The relationship between the vertical and lateral displacements and the pile diameter (D) at different the distances between the tunnel and pile (S= 8.3, 12.5, and 16.5) m with pile length a) L= 11 m, b) L= 20 m, and c) L=30 m**

According to Fattah et al. (2011) [33], boring a tunnel will cause the lateral earth pressure coefficient to drop. The vertical displacement, the width of the settling trough, and the excess pore water pressure all rise when a zone with a lower $k_0$ is used. Only a zone with a diameter equal to the tunnel can experience this effect.

The current conclusions are consistent with those of Nawel et al. (2021) [34], who discovered that the displacements and stresses produced on the tunnel lining decrease as the distance between piles and tunnels increases, pile location/length from the tunnel, the diameter of the pile, and piles number.

Figure 10 illustrates the increase in the maximum bending moment induced in the tunnel line with pile length.

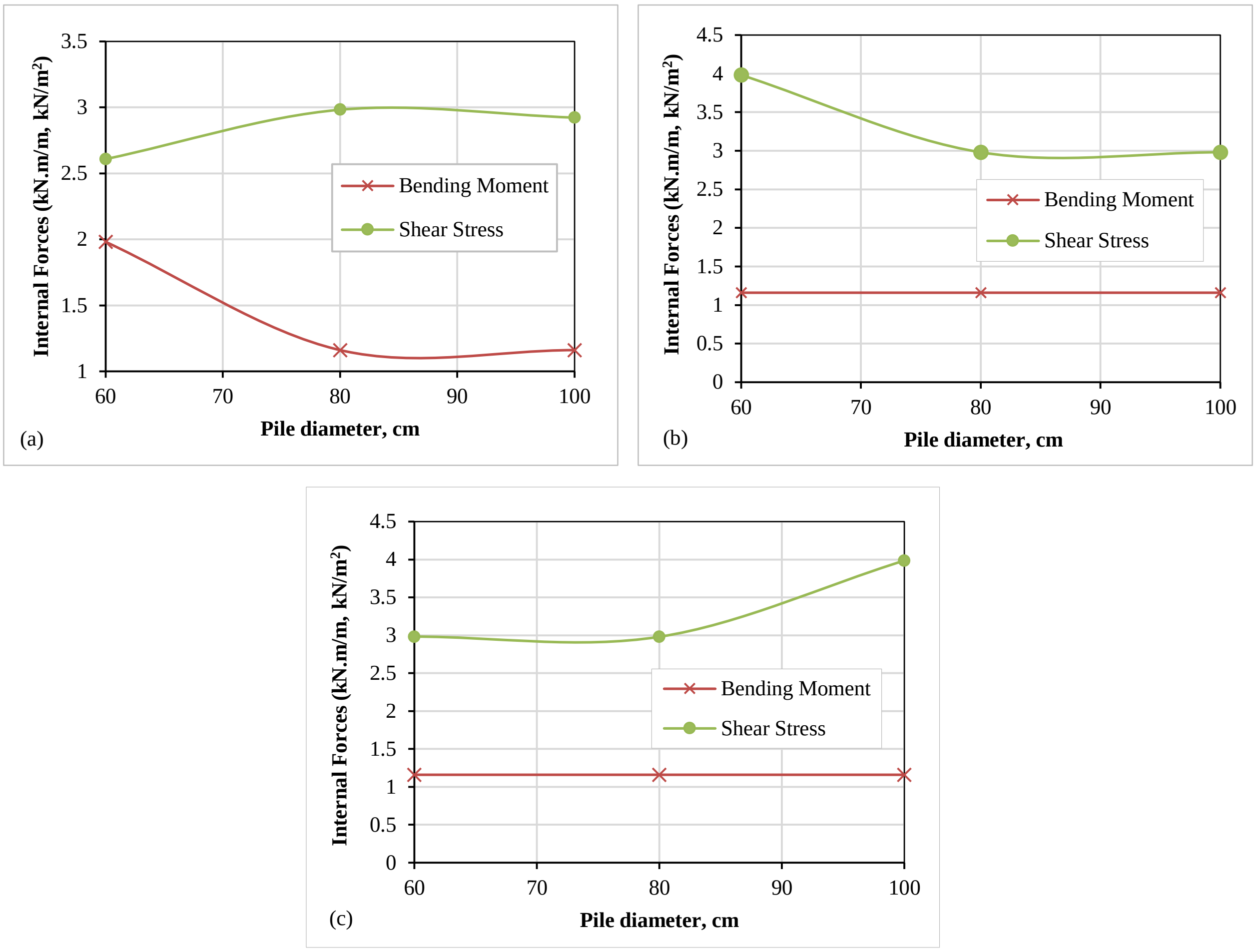
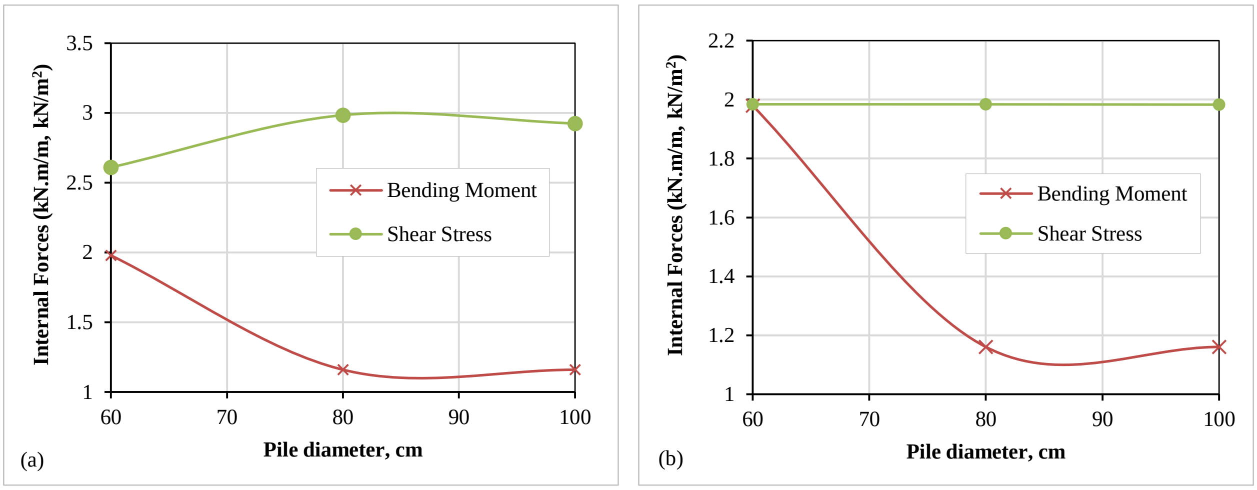



**Figure 10. Bending moment and shear stress in the tunnel lining relative to pile diameter with the pile length a) L=11 m, b) L= 20 m, and c) L=30 m with constant the distance between tunnel and pile (S= 8.3 m)**

Figure 11 reveals that both the shear stress and bending moment decrease with increase of spacing between the pile and tunnel. Figure 12 illustrates that there is an increase in the shear force developed in the tunnel lining with pile diameter for different spacings between the tunnel and pile. This increase becomes smaller as the length of the pile increases



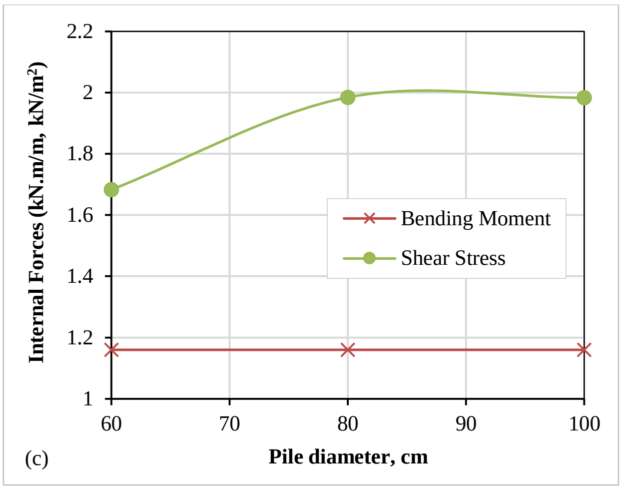



**Figure 11. Bending moment and shear stress in the tunnel lining relative to pile diameter with the distance between tunnel and pile a) S = 8.3 m, b) S = 12.5 m, and c) S = 16.5m with constant pile length (L = 11 m)**

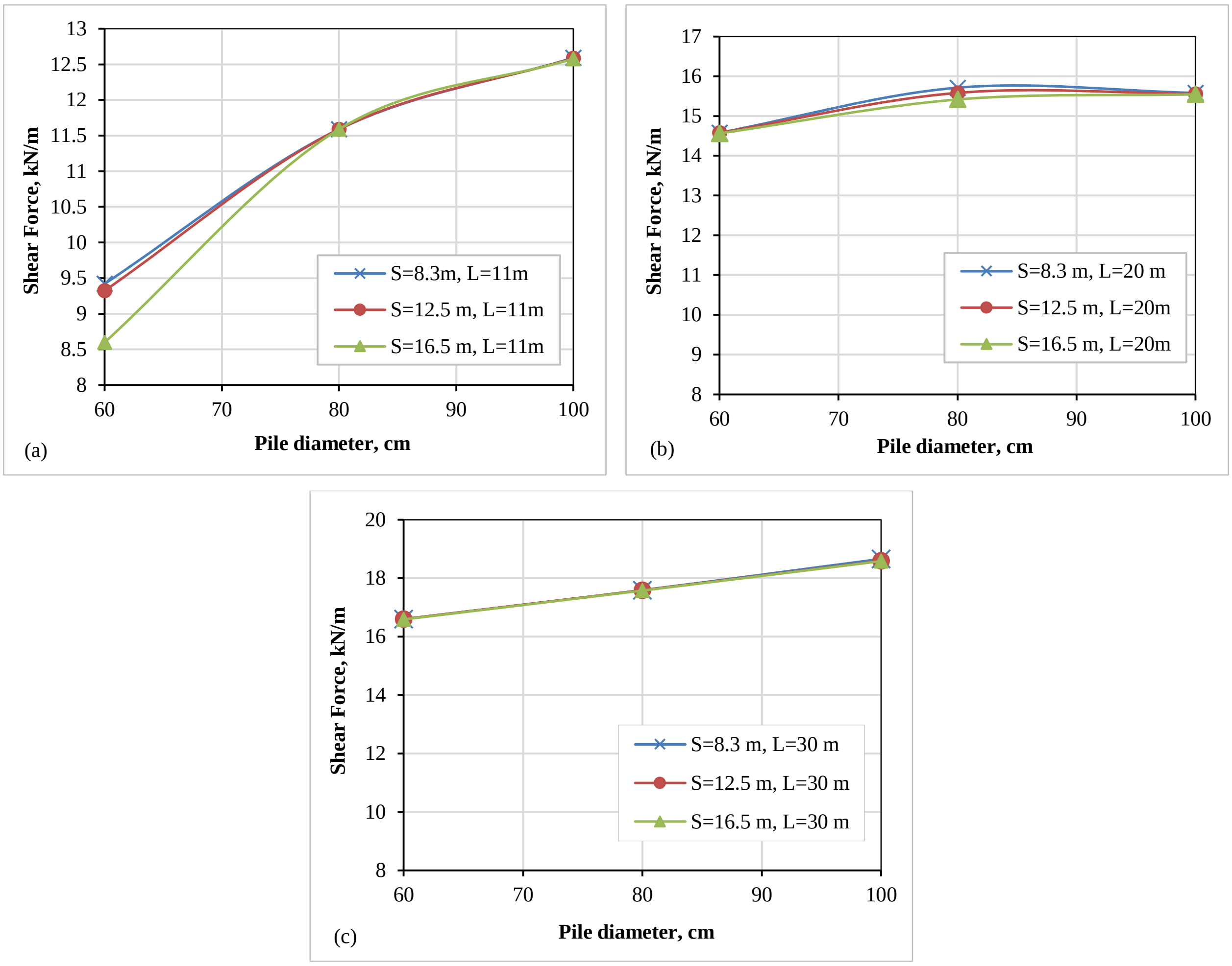



**Figure 12. Shear force in the tunnel lining relative to pile diameter with different distances between tunnel and pile (S=8.3, 12.5, and 16.5) m and pile length equal to a) 11 m, b) 20 m, and c) 30 m**

## 3.3. Effect of Pile Length

Figure 13 demonstrates that there is a slight increase in both the horizontal and vertical displacements with an increase in pile length for different pile diameters and spacings between the pile and the tunnel. Figure 14 reveals that at small spacing between the pile and tunnel (8.3 m and 12.5 m), the bending moment in the tunnel lining decreases with pile length increase.

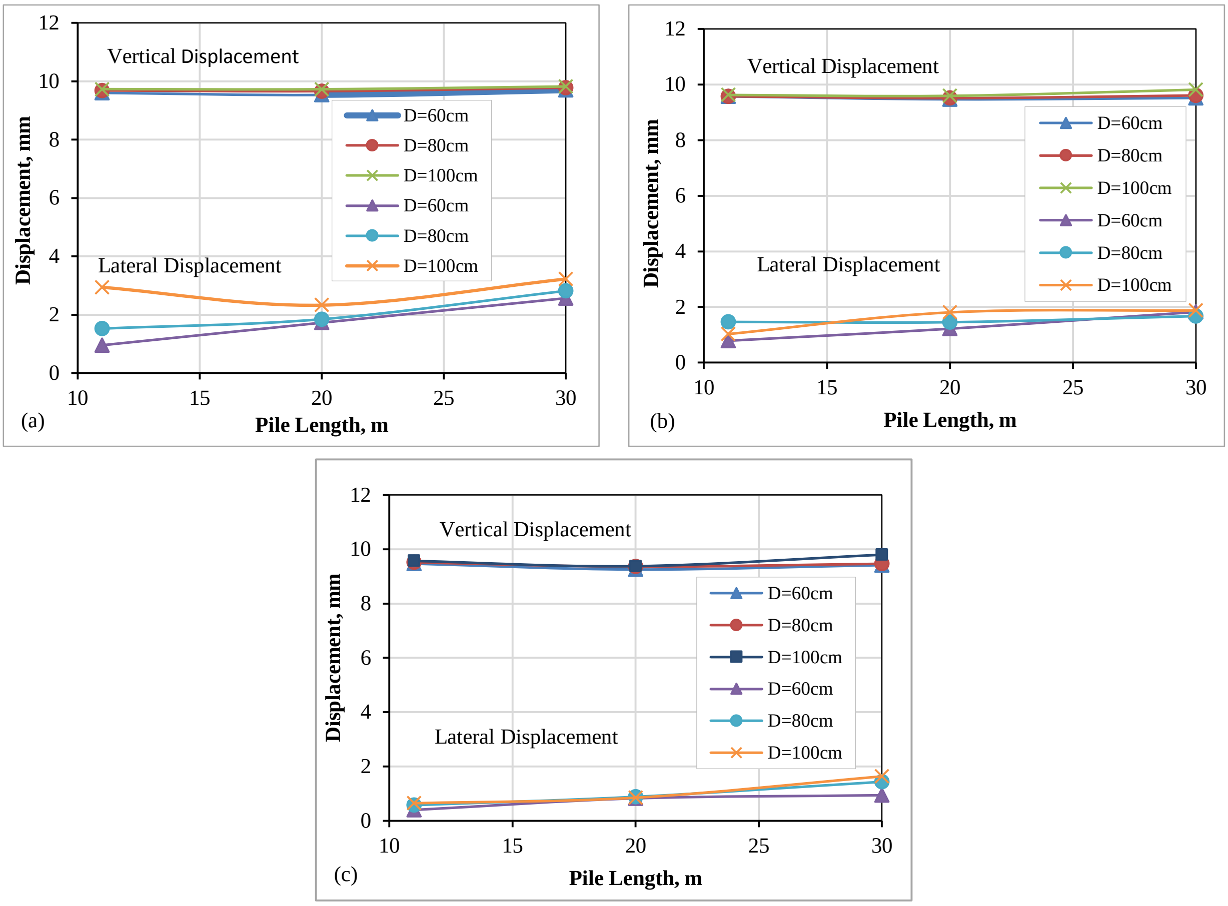



**Figure 13. The relationship between the vertical and lateral displacements and the pile length (L) at different pile diameter (D= 60, 80, and 100 cm with the distances between tunnel and pile a) S= 8.3 m, b) S= 12.5 m, and c) S =16.5 m**

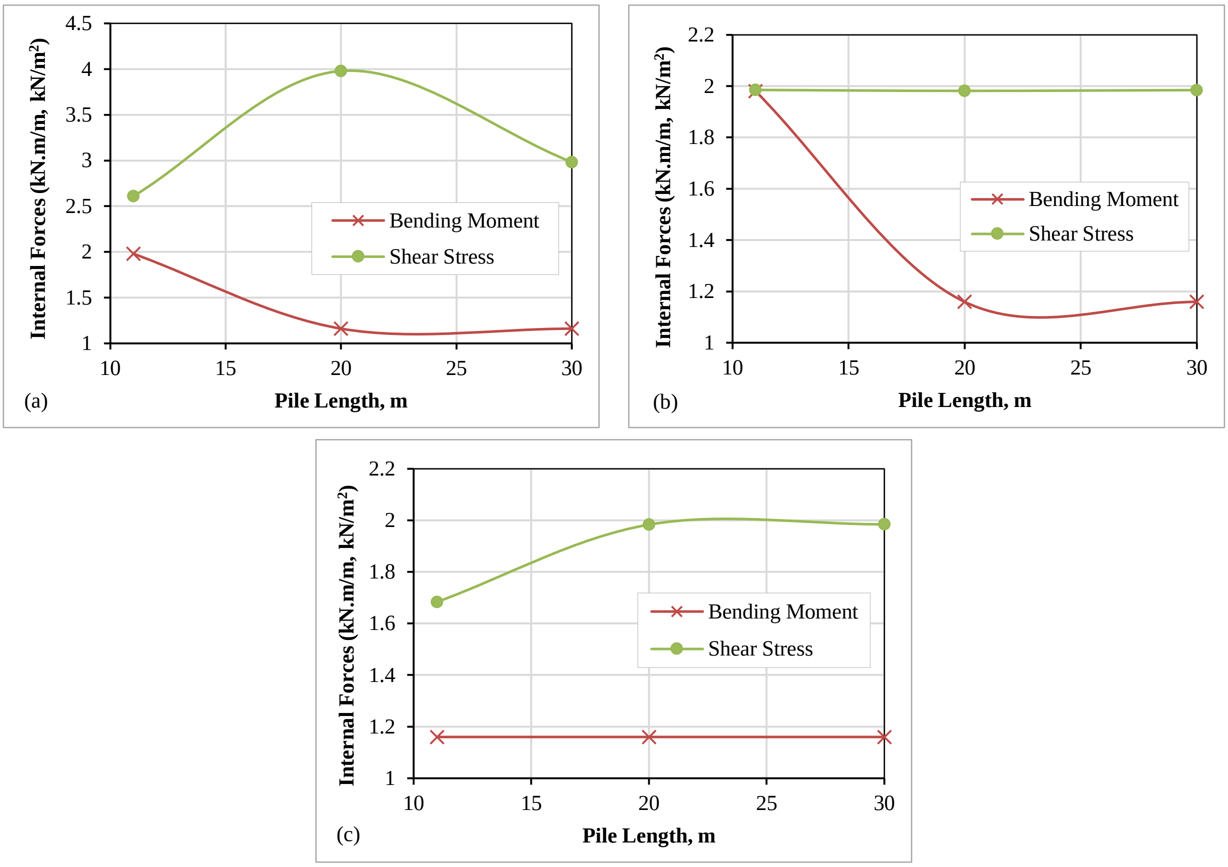



**Figure 14. Bending moment and shear stress in the tunnel lining relative to pile length with the distance between tunnel and pile a) S=8.3 m, b) S=12.5 m, and c) S=16.5 m with constant pile diameter (D = 60 cm)**

Figure 15 shows that the bending moment decreases when the pile diameter increases while Figure 16 depicts the effect of pile length on the shear force generated in the lining where it increases with pile length for all pile diameters and distances between the pile and tunnel.

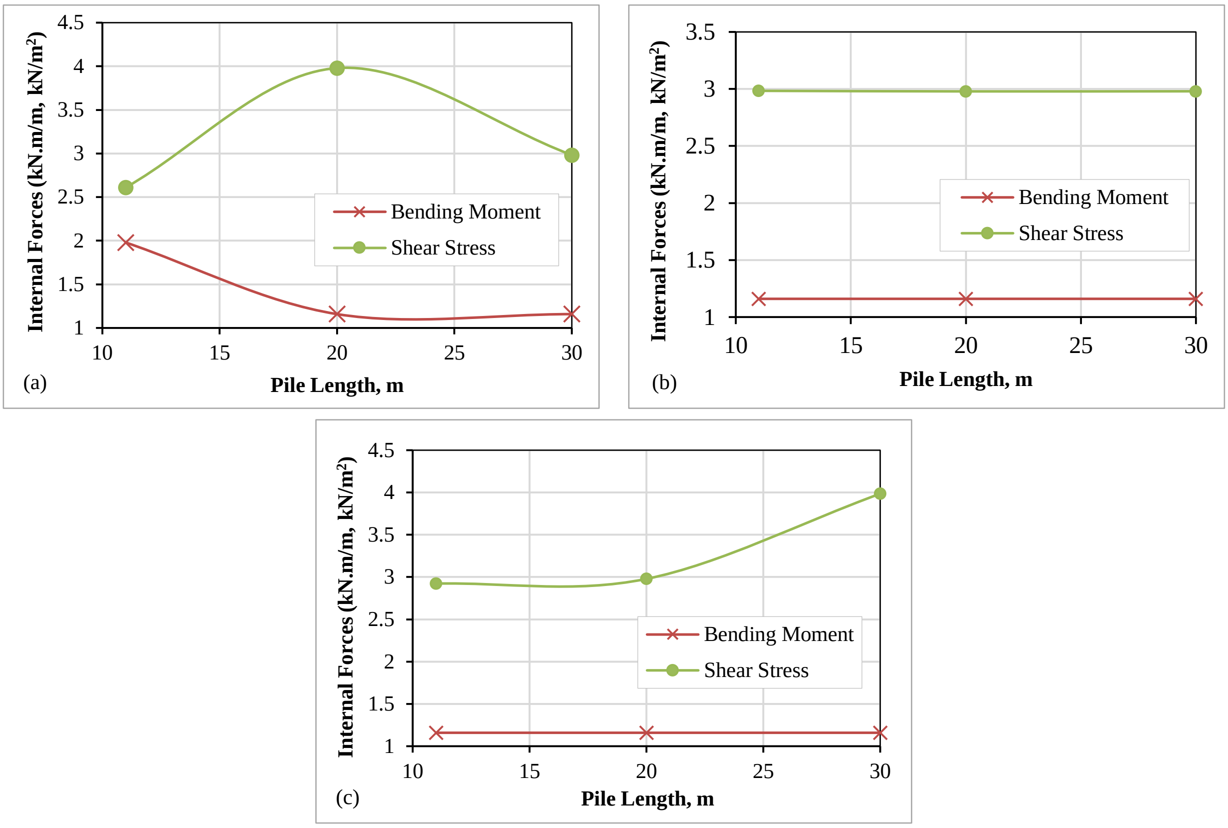



**Figure 15. Bending moment and shear stress in the tunnel lining relative to pile length with the pile diameter a) D = 60 cm, b) D = 80 cm, and c) D = 100 cm with constant the distance between tunnel and pile (S = 8.3 m)**

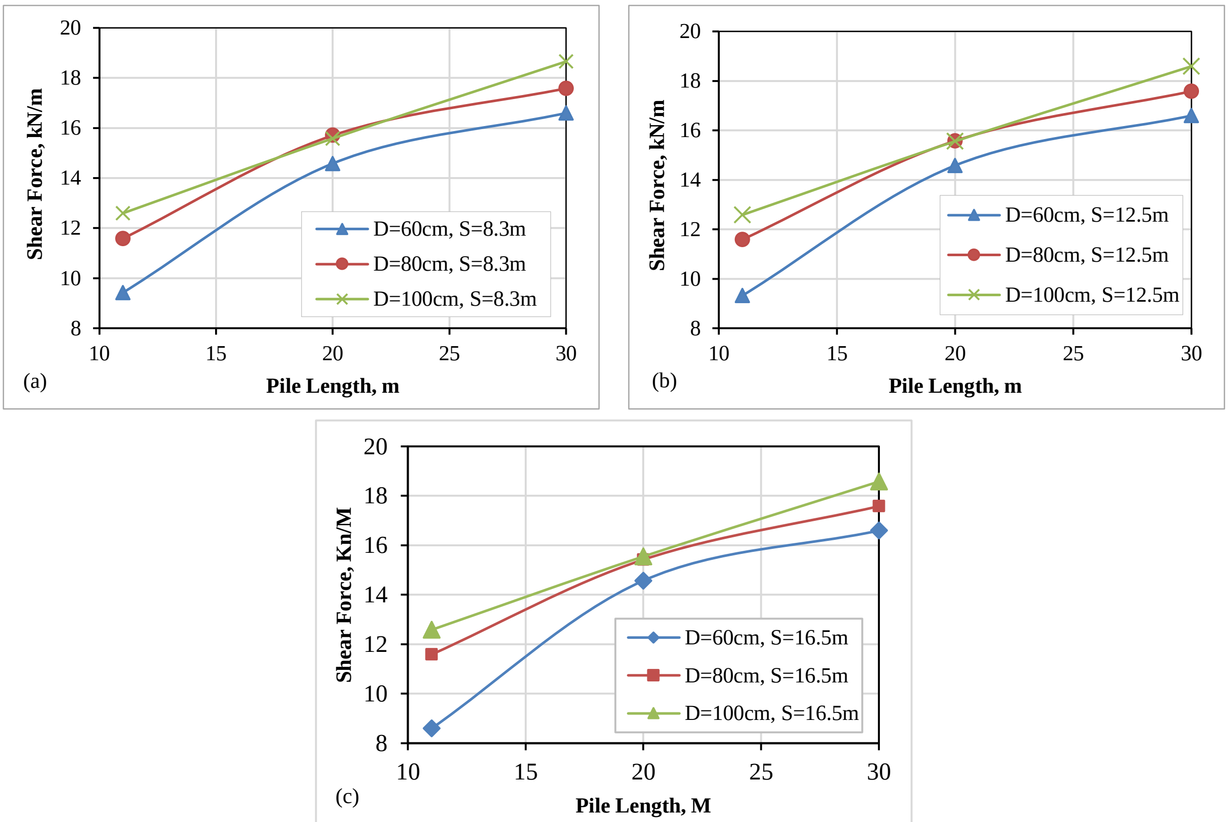



**Figure 16. Shear force in the tunnel lining relative to pile length with different pile diameter (D=60, 80, and 100) cm and the distances between tunnel and pile equal to a) 8.5 m, b) 12.5 m, and c) 16.5 m**

## 4. Conclusion

An increased demand for infrastructure is a result of the expansion of numerous cities. Subsurface construction, including tunnels, is becoming more effective at delivering the necessary infrastructure as urban space gets more constrained. Therefore, a 3-D model was established utilizing a modified Mohr-Coulomb constitutive model for the soil layers to model the behavior of soil surrounding a tunnel affected by the construction of a nearby bored pile. In addition, various factors affecting the tunnel response were studied, including the location of the pile tip relative to the tunnel centerline, the diameter, and the length of the pile. The conclusions could be obtained as the vertical displacement is always larger than the horizontal displacement. This may be due to the vertical overburden pressure. Also, the pile length and diameter seem to not affect both the horizontal and vertical displacements. Furthermore, the bending moment decreases as the distance from the tunnel increases from 8 to 12 m and then remains constant, while the shear stress is not affected considerably. The shear stress and bending moment increase with pile diameter and length due to the increased confinement caused by the pile. On the other hand, the spacing has a considerable effect on the horizontal displacement with very little effect on the vertical displacement. Additionally, there is an increase in the shear force developed in the tunnel lining with pile diameter for different spacings between the tunnel and pile. This increase becomes smaller as the length of the pile increases. Finally, at the small spacing between the pile and tunnel (8.3 m and 12.5 m), the bending moment in the tunnel lining decreases as the pile length increases.

## 5. Declarations

### 5.1. Author Contributions

Conceptualization, M.A., M.F., and M.H.; methodology, M.A.; software, M.A.; validation, M.A. and M.F.; formal analysis, M.A.; investigation, M.A., M.H., and M.F.; resources, M.A. and M.F.; data curation, M.A. and M. F.; writing—original draft preparation, M.A., M.H., and M.F.; writing—review and editing, M.A. and M.F.; supervision, M.F. All authors have read and agreed to the published version of the manuscript.

### 5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

### 5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### 5.4. Conflicts of Interest

The authors declare no conflict of interest.

## 6. References

[1] Admiraal, H., & Cornaro, A. (2016). Why underground space should be included in urban planning policy - And how this will enhance an urban underground future. Tunnelling and Underground Space Technology, 55, 214–220. doi:10.1016/j.tust.2015.11.013.

[2] Goh, A. T. C., Zhang, W., Zhang, Y., Xiao, Y., & Xiang, Y. (2018). Determination of earth pressure balance tunnel-related maximum surface settlement: a multivariate adaptive regression splines approach. Bulletin of Engineering Geology and the Environment, 77(2), 489–500. doi:10.1007/s10064-016-0937-8.

[3] von der Tann, L., Sterling, R., Zhou, Y., & Metje, N. (2020). Systems approaches to urban underground space planning and management – A review. Underground Space (China), 5(2), 144–166. doi:10.1016/j.undsp.2019.03.003.

[4] Ayasrah, M., Qiu, H., Zhang, X., & Daddow, M. (2020). Prediction of ground settlement induced by slurry shield tunnelling in granular soils. Civil Engineering Journal (Iran), 6(12), 2273–2289. doi:10.28991/cej-2020-03091617.

[5] Zhang, H.-B., Chen, J.-J., Fan, F., & Wang, J.-H. (2017). Deformation Monitoring and Performance Analysis on the Shield Tunnel Influenced by Adjacent Deep Excavations. Journal of Aerospace Engineering, 30(2), B4015002. doi:10.1061/(asce)as.1943-5525.0000574.

[6] Qiu, H., Zhou, Y., & Ayasrah, M. (2023). Impact Study of Deep Foundations Construction of Inclined and Straight Combined Support Piles on Adjacent Pile Foundations. Applied Sciences (Switzerland), 13(3), 1810. doi:10.3390/app13031810.

[7] Pujadas-Gispert, E., Sanjuan-Delmás, D., de la Fuente, A., Moonen, S. F., & Josa, A. (2020). Environmental analysis of concrete deep foundations: Influence of prefabrication, concrete strength, and design codes. Journal of Cleaner Production, 244, 118751. doi:10.1016/j.jclepro.2019.118751.

[8] Mair, R. J., Taylor, R. N., & Bracegirdle, A. (1993). Subsurface settlement profiles above tunnels in clays. Geotechnique, 43(2), 315–320. doi:10.1680/geot.1993.43.2.315.

[9] Ng, C. W. W., Lu, H., & Peng, S. Y. (2013). Three-dimensional centrifuge modelling of the effects of twin tunnelling on an existing pile. Tunnelling and Underground Space Technology, 35, 189–199. doi:10.1016/j.tust.2012.07.008.

[10] Jongpradist, P., Kaewsri, T., Sawatparnich, A., Suwansawat, S., Youwai, S., Kongkitkul, W., & Sunitsakul, J. (2013). Development of tunneling influence zones for adjacent pile foundations by numerical analyses. Tunnelling and Underground Space Technology, 34, 96–109. doi:10.1016/j.tust.2012.11.005.

[11] Xu, Q., Zhu, H., Ma, X., Ma, Z., Li, X., Tang, Z., & Zhuo, K. (2015). A case history of shield tunnel crossing through group pile foundation of a road bridge with pile underpinning technologies in Shanghai. Tunnelling and Underground Space Technology, 45, 20–33. doi:10.1016/j.tust.2014.09.002.

[12] Yao, J., McNamara, A., & Taylor, R. (2008). The effects of loaded bored piles on existing tunnels. Geotechnical Aspects of Underground Construction in Soft Ground, CRC Press, 751-758.

[13] Salim, N. M., & Lafta, S. J. (2020). The Effect of Group of Piles on Existing Tunnel. IOP Conference Series: Materials Science and Engineering, 737(1), 12093. doi:10.1088/1757-899X/737/1/012093.

[14] Boldini, D., Losacco, N., Bertolin, S., & Amorosi, A. (2016). Modelling of Reinforced Concrete Framed Structures Interacting with a Shallow Tunnel. Procedia Engineering, 158, 176–181. doi:10.1016/j.proeng.2016.08.425.

[15] Lasciarrea, W. G., Amorosi, A., Boldini, D., de Felice, G., & Malena, M. (2019). Jointed Masonry Model: A constitutive law for 3D soil-structure interaction analysis. Engineering Structures, 201, 109803. doi:10.1016/j.engstruct.2019.109803.

[16] Lai, H., Zheng, H., Chen, R., Kang, Z., & Liu, Y. (2020). Settlement behaviors of existing tunnel caused by obliquely under-crossing shield tunneling in close proximity with small intersection angle. Tunnelling and Underground Space Technology, 97, 103258. doi:10.1016/j.tust.2019.103258.

[17] Yin, Q., Xin, T., Zhenggang, H., & Minghua, H. (2023). Measurement and Analysis of Deformation of Underlying Tunnel Induced by Foundation Pit Excavation. Advances in Civil Engineering, 2023, 1–12. doi:10.1155/2023/8897139.

[18] Mahajan, S., Sharma, A., Ayothiraman, R., & Sharma, K. G. (2023). Three-Dimensional Physical Modeling of Response of Existing Metro Tunnel to Pile Loading in Delhi Silt in India. Practice Periodical on Structural Design and Construction, 28(2), 04023008. doi:10.1061/ppscfx.sceng-1159.

[19] Jeon, Y.-J., Kim, S.-H., Kim, J.-S., & Lee, C.-J. (2017). A study on the effects of ground reinforcement on the behaviour of pre-existing piles affected by adjacent tunnelling. Journal of Korean Tunnelling and Underground Space Association, 19(3), 389–407. doi:10.9711/ktaj.2017.19.3.389.

[20] Yoo, C. (2014). Three dimensional numerical investigation on the effect of bridge construction on existing tunnel. KSCE Journal of Civil Engineering, 18(3), 794–802. doi:10.1007/s12205-014-0361-1.

[21] Lueprasert, P., Jongpradist, P., Jongpradist, P., & Suwansawat, S. (2017). Numerical investigation of tunnel deformation due to adjacent loaded pile and pile-soil-tunnel interaction. Tunnelling and Underground Space Technology, 70, 166–181. doi:10.1016/j.tust.2017.08.006.

[22] Lueprasert, P., Jongpradist, P., Jongpradist, P., & Schweiger, H. F. (2023). Structural Responses of a Tunnel Lining Due to an Adjacent Loaded Pile. International Journal of Civil Engineering, 21(6), 1027–1043. doi:10.1007/s40999-023-00821-9.

[23] Zheng, G., Du, Y., Cheng, X., Diao, Y., Deng, X., & Wang, F. (2017). Characteristics and prediction methods for tunnel deformations induced by excavations. Geomechanics and Engineering, 12(3), 361–397. doi:10.12989/gae.2017.12.3.361.

[24] Zhuang, Y., Cui, X., & Hu, S. (2023). Numerical simulation and simplified analytical method to evaluate the displacement of adjacent tunnels caused by excavation. Tunnelling and Underground Space Technology, 132, 104879. doi:10.1016/j.tust.2022.104879.

[25] Lim, C. B., Jusoh, S. N., Lim, C. X., Abang Hasbollah, D. Z., & Sohaei, H. (2023). Tunnel – Pile interaction sequence: Parametric studies. Physics and Chemistry of the Earth, 129, 103312. doi:10.1016/j.pce.2022.103312.

[26] Möller, S. C., & Vermeer, P. A. (2008). On numerical simulation of tunnel installation. Tunnelling and Underground Space Technology, 23(4), 461–475. doi:10.1016/j.tust.2007.08.004.

[27] Ayasrah, M., Qiu, H., & Zhang, X. (2021). Influence of Cairo metro tunnel excavation on pile deep foundation of the adjacent underground structures: Numerical study. Symmetry, 13(3), 426. doi:10.3390/sym13030426.

[28] Nainegali, L., Basudhar, P. K., & Ghosh, P. (2021). Interference of proposed footing with an existing footing resting on non-linearly elastic dense and loose cohesionless soil bed. European Journal of Environmental and Civil Engineering, 25(14), 2574-2591. doi:10.1080/19648189.2019.1638311.

[29] Qiu, H., Wang, Z., Ayasrah, M., Fu, C., & Gang, L. (2022). Numerical Study on the Reinforcement Measures of Tunneling on Adjacent Piles. Symmetry, 14(2), 288. doi:10.3390/sym14020288.

[30] Graine, N., Hjiaj, M., & Krabbenhoft, K. (2021). 3D failure envelope of a rigid pile embedded in a cohesive soil using finite element limit analysis. International Journal for Numerical and Analytical Methods in Geomechanics, 45(2), 265–290. doi:10.1002/nag.3152.

[31] Surarak, C., Likitlersuang, S., Wanatowski, D., Balasubramaniam, A., Oh, E., & Guan, H. (2012). Stiffness and strength parameters for hardening soil model of soft and stiff Bangkok clays. Soils and Foundations, 52(4), 682–697. doi:10.1016/j.sandf.2012.07.009.

[32] Fattah, M. Y., Shlash, K. T., & Salim, N. M. (2013). Prediction of settlement trough induced by tunneling in cohesive ground. Acta Geotechnica, 8(2), 167–179. doi:10.1007/s11440-012-0169-4.

[33] Fattah, M. Y., Shlash, K. T., & Salim, N. M. (2011). Effect of reduced $k_0$ zone on time-dependent analysis of tunnels. Advances in Civil Engineering, 2011, 1–12. doi:10.1155/2011/963502.

[34] Nawel, B., Salah, M., & Noura, H. (2021). A simplified 3D model for existing tunnel response to piles construction. Selected Scientific Papers - Journal of Civil Engineering, 16(2), 87–103. doi:10.2478/sspjce-2021-0018.