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Study of the Effect of Tunnelling on the Ground Movement and the Behaviour of Resting Structures

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Keywords
Tunneling, Raft foundation, Ground surface settlement, bending moment, Tunnel spacing, PLAXIS.

Abstract: Designing tunnels in urban areas necessitates an accurate estimation of their construction effects on adjacent structures. This study explores tunnelling impacts beneath raft foundations, focusing on settlement and bending moment variations due to different tunnel depths and soil densities. A verification model validated tunnel modelling with field data, employing a 2D finite element model to assess raft foundation performance above tunnels. It also examines the influence of tunnel depth, soil consistency, and spacing of two tunnels. Key results show raft settlement increasing by over 250% when tunnels are directly below at a 7.5 m depth, regardless of soil density. Soil cover thickness above the tunnel significantly affects the raft's bending moment, with an increase of up to 400% and 300% for 5 m and 7.5 m cover depths, respectively. Final tunnel construction stage settlements varied with soil density. The study also reveals that increasing the spacing between closely spaced tunnels beyond 1.2 diameters reduces both raft settlements and bending moments. These findings emphasize the importance of careful tunnel placement and soil cover management to minimize negative impacts on raft foundations.

1. Introduction

Underground transit routes are becoming crucial in urban environments with dense traffic and limited space. Tunnelling activities in urban areas are always associated with surface and subsurface ground subsidence, which may affect the stability of nearby structures and utilities.

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The necessity of constructing tunnels beneath or close to existing structures is integral to these systems, and numerous researchers have delved into this topic (Ding et al., 2019; Rajabi et al., 2021; Shahin et al., 2016; Wu et al., 2024; Ding et al. 2019; Rajabi et al., 2021; Shahin et al., 2016; Wu et al., 2024). During and after tunnel construction, the surrounding building is subjected to different deformations and strains due to immediate settlement. The constructed buildings should be able to bear the effect of change in the total, differential settlement, and bending moment of the raft according to the tunneling activity. The soil settlement around the tunnel and the ground movement above the tunnel should be taken into consideration too.

Mroueh and Shahrour (2003) have emphasized the substantial challenges that arise when designing and constructing tunnels, particularly in soft ground and shallow depths, and their proximity to existing structures. Anticipating additional settlements and straining actions induced by tunneling has become a crucial consideration in the planning phase. Peck (1969) derived simple empirical equations from Greenfield site data, and similar relationships were proposed by other researchers to predict settlement profiles in such areas (O'Reilly and New 1982; Sugiyama et al. 1999). However, this method has limitations, neglecting factors like the stiffness of structures, interaction between tunnelling and adjacent structures, and the three-dimensional aspect of the problem. In contrast, the "Coupled Analysis technique," utilizing finite element modelling (Mroueh and Shahrour 2003), enables the simulation of intricate interactions between tunnels and structures, considering various geometric configurations. Tunneling-induced ground movements primarily depend on the spatial geometries of the tunnel, geological conditions, and the behaviors of the tunnel boring machine (TBM) during the tunneling process. Traditionally, various methods have been used to estimate these movements, including empirical approaches (Mair and Taylor 1999; Peck 1969), analytical methods (Loganathan and Poulos 1998; Pinto and Whittle 2014), and numerical simulations (Avgerinos et al. 2018; Kasper and Meschke 2004; Komiya et al. 1999). While each method offers different approaches, the crucial inputs always revolve around the tunnel's spatial geometries and geological conditions. However, it's worth noting that the effects of TBM behaviors have not received much attention in these estimations.

While the paper focuses on the settlement of raft foundations due to tunneling, similar settlement patterns can have significant implications for the structural integrity of other infrastructures, such as buildings. Settlement, particularly when uneven or differential, can lead to a range of structural issues. These include cracking in walls and foundations, misalignment of doors and windows, and, in severe cases, structural failure. For multi-storey buildings, uneven settlement can induce additional stresses in the structural frame, potentially leading to tilting or leaning of the structure. Infrastructure such as pipelines, roads, and bridges in the vicinity of tunneling activities may also be affected, experiencing distortions that could disrupt services or require costly repairs. Moreover, the interaction between the tunnel-induced ground movements and the existing structures can lead to changes in groundwater flow patterns, possibly exacerbating settlement issues or affecting the durability of underground structures through increased moisture penetration. Understanding and mitigating these effects is crucial for maintaining the safety and functionality of urban infrastructure in areas affected by tunneling activities.

This paper investigates the interaction between tunnels and adjacent structures to assess the performance of a raft foundation during the tunnel boring process using 2D numerical finite element models. The model output has been validated through a comparison with the field measurements of the settlement trough recorded during the construction of the Second Heinenoord tunnel in the Netherlands (1998). This paper studies the influence of various parameters such as soil stiffness, tunnel cover, horizontal clearance between the raft foundation and tunnel, and the case of executing two tunnels on the raft settlement.

2. Numerical simulation

2.1. Verification model

The 2D numerical model was conducted by using PLAXIS 2D to simulate the Second Heinenoord Tunnel (after Moller 2006). The 3D model's geometry from Moller (2006) was used in the 2D analysis, but the third dimension in the tunnel's longitudinal direction was neglected. Consequently, the tunnel is simulated as a plane strain model in the 2D analysis. The same soil and water conditions as the 3D model by Moller (2006) were employed in the 2D model. To save time and take advantage of tunnel symmetry, only half of the tunnel was simulated. In this analysis, four fill layers were simulated (Figure 1). Starting from the top, there is a fill layer with a thickness of 4m, followed by two layers of sand with thicknesses of 15.75m and 3.5m, respectively. The bottom layer comprises clay with a thickness of 4.25m. The tunnel was entirely excavated within sand layers with an outer diameter of 8.3m and an inner diameter of 7.9. The bottom border is constrained in both directions, while the side boundaries are restrained horizontally.

The groundwater table, GWT, is encountered at a depth of 1.5 m below the ground surface. The model's total width in the X-direction is 40 m, ranging from X = -40 m to X = Zero at the tunnel centreline. The model's total depth in the Y-direction is 27.5 m, starting from Y = zero at the ground surface and going down to Y = -27.5 m. These dimensions were selected as a function of the tunnel diameter, tunnel depth, and foundation width to consider the effect of boundary conditions (Moller 2006). The grouting pressure is simulated as a radial pressure of 133 kPa at the tunnel crown, increasing linearly with depth by 15 kPa (ElMouchi et al. 2017). The interface material is a non-porous linear elastic material with a Young's Modulus of 6×10^7 kN/m^2 and a Poisson's ratio (υ) of 0.15 (Schädlich and Schweiger 2014b). The tunnel lining is simulated as a linear elastic concrete material, using a shell element with a flexural rigidity, EI = 26.78 $MN.m^2$, normal stiffness, EA = 5×10^3 MN, weight, w = 24 kN/m^2, and Poisson's ratio $\upsilon = 0.15$. The grouting pressure is applied as a radial pressure on this interface material. The raft was simulated using an elastic beam element with bending stiffness, EI, and axial stiffness, EA of 1.67×10^6 MN and 20×10^7 MN, respectively.

The interface between soil and concrete liner was defined using interface element and using R_{inter} of 0.67 (ElMouchi et al. 2017). 15 noded triangular elements have been chosen which results in a two-dimensional finite element model with two translational degrees of freedom per node. Mesh sensitivity was assessed to determine the optimal mesh thickness that prevents changes in settlement values due to coarse mesh size. The results show that using a fine mesh size will mitigate any effects of the mesh size on the model results.

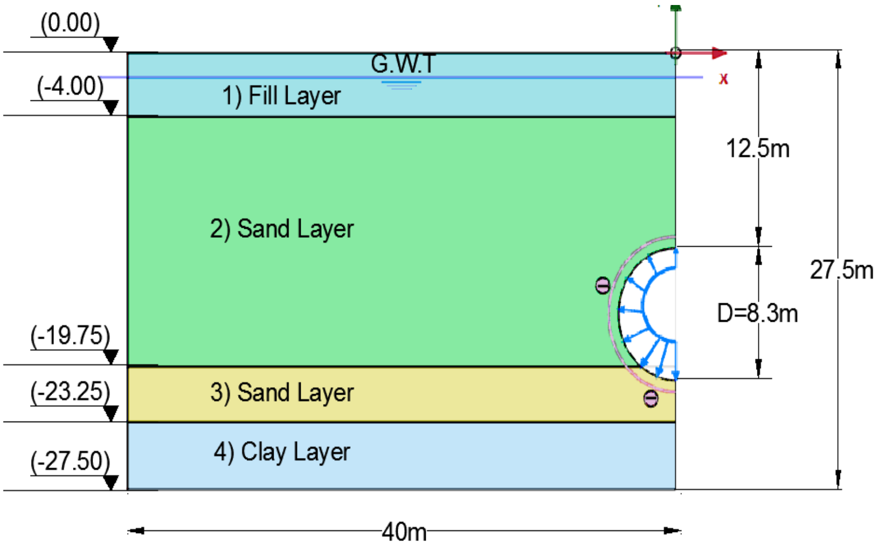

Fig. 1: 2D Model Geometry of the Second Heineneoord Tunnel after Moller (2006)

Table 1 lists the parameters of soil layers applied in the numerical model for the Second Heinenoord Tunnel (Modified from Moller, 2006).

Table 1: lists the parameters of soil layers applied in the numerical model for the Second Heinenoord Tunnel (Modified from Moller, 2006)

Layer	**(1) Fill**	**(2) Sand layer I**	**(3) Sand layer II**	**(4) Clay**
Soil Model	Hardening soil			
Depth(m)	(0) to (-4.0)	(-4.0) to (-19.75)	(-19.75) to (-23.25)	(-23.25) to (-27.5)
γ (kN/m^3)	17.2	20	20	20
E^{ref}_{50} (MPa)	14	35	35	12
E^{ref}_{oed} (MPa)	14	35	35	7
E^{ref}_{ur} (MPa)	42	105	105	35
Stress power (m)	0.5	0.5	0.5	0.9
$C^{/}$ (kPa)	3	0.01	0.01	7
$\varphi^{/}$ [°]	27	35	35	31
υ_{ur}	0.2	0.2	0.2	0.2
$K_o = 1\text{-}\sin\varphi^{/}$	0.58	0.47	0.47	0.55
OCR	1	1	1	1
P_{ref} (kPa)*	65	65	65	65
Dilation angle (ψ) [°]	--	5	5	1

*(ElMouchi et al. 2017)

DE confinement is defined by the factor $(1-\beta)$. The objective is for the initial stresses, σ_{ini}, acting around the tunnel's location, to be split such that $(1-\beta)\ \sigma_{ini}$ is applied to the unsupported tunnel portion, and $\beta.\sigma_{ini}$ is applied when the tunnel lining is present. To model the tunnel's construction, a Staged Construction calculation is required. During this, the tunnel lining gets activated, the soil clusters inside the tunnel are deactivated, and the DE confinement values are configured.

Although the β-method offers a straightforward approach for 2D tunneling simulations, designers should exercise caution when using it. One significant challenge is that the precise value of β is often not immediately apparent. This value can usually only be ascertained through 3D modelling or multiple 2D trials aimed at replicating the behavior of the 3D model. It's also worth noting that a single β value may not accurately represent all aspects of the model. For example, one β value may produce an accurate settlement trough at the ground surface but fail to correctly capture the strain forces in the tunnel lining. Consequently, some experts recommend using different β values within the same model (Laabmayr and Swoboda 1986; Indra 2021; PLAXIS Manual 2022). However, the efficacy of this approach relies on either accurate 3D models or field measurements. Although a typical β value of 0.5 is commonly used in engineering practices, this could lead to inaccurate predictions for both the settlement trough and strain forces in the tunnel lining.

The choice of a DE confinement factor (β-value) is crucial for accurately modelling the stress redistribution around the tunnel during excavation. The β-value essentially represents the proportion of the original in-situ stress that is maintained around the tunnel after its construction. A lower β-value, such as 0.1, indicates a greater reduction of confining stress around the tunnel, suggesting significant stress relief and potentially larger deformations or settlements.

In the verification model, a β value of 0.1 is employed, which is considerably lower than the generally recommended value of 0.5. The difference between these two β values suggests that the commonly recommended β value of 0.5 could serve as an initial estimate during the conceptual design phase for the soil-tunnel interaction.

Choosing a β-value of 0.1 in the verification model could be attributed to specific project requirements, field observations, or the nature of the geological and geotechnical conditions encountered. This selection might be based on detailed analyses or empirical evidence indicating that the standard value of 0.5 does not sufficiently represent the actual behavior of the soil and tunnel interaction for the specific case study. For instance, a lower β-value might better simulate the observed ground movements or the response of the soil to tunneling in soft ground conditions or in scenarios where significant stress relaxation is anticipated around the tunnel. Comparatively, the widely accepted β-value of 0.5 is often used as a general approximation for many tunneling projects, assuming moderate stress relief and deformation around the tunnel. This value is considered a balanced choice for a variety of soil conditions, tunnel depths, and construction methodologies, providing a reasonable estimate of ground behavior in the absence of more specific data.

Figure 2 compares the results of the surface settlement of the 2D model with the field measurements, 2D model using β of 0.5 and 0.1. From the results of the PLAXIS 2D model, the 2D model could predict the high settlement of the surface, while the settlement may be under-predicted values for the settlement, but the maximum difference of 4mm which is a low value compared to the maximum settlement of 26mm.

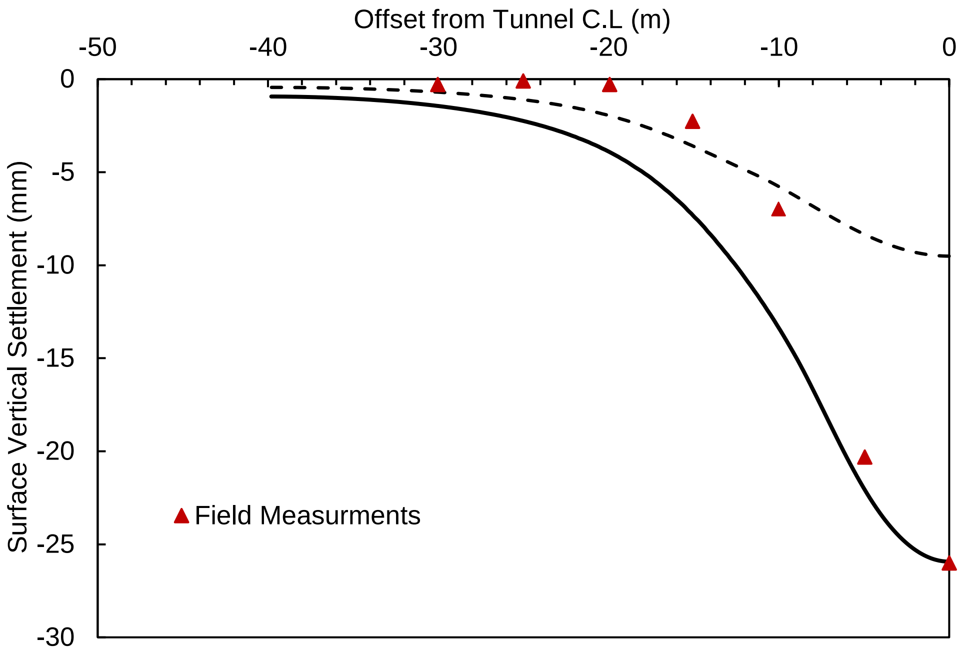

Fig. 2: Comparing Various Surface Settlement Troughs for the Second Heinenoord Tunnel after 2D Verification Using β-Method.

3. Parametric study

The current study focuses on a specific tunnel with an outer diameter of 7.50 m and a soil cover of 7.50 m, as depicted in Figure 3. The model dimensions are provided for the X and Y directions, along with details about the interface material and grouting pressure. The 2D model consists of two construction stages. In the first stage, initial vertical and horizontal stresses are generated using the at-rest earth pressure coefficient K_0. The soil stratigraphy was modelled initially to simulate the stage before the beginning of any construction work. In PLAXIS, initial stresses may be generated by using the K_0 procedure, the Gravity loading, or the Field stress. These options are available in the Calculation type in the initial phase. The K_0 procedure is used to define the initial stresses for the model, considering the loading history of the soil.

The second stage involves deactivating the excavation volume of the tunnel, performing dewatering to keep the cluster dry, activating the interface around the tunnel, and applying the grouting pressure. The β value in this model is 0.5, commonly used in engineering practice. The proposed raft configuration includes dimensions of 20m in length and 1m in thickness, with column spacing of 4.5m.

The building's inner column load is 270kN, and the outer column load is 195kN. These column loads are modelled as line loads in the 2D model by dividing the column load by the spacing between columns perpendicular to the examined section. Therefore, the inner and outer column loads are defined as 60kN/m and 43.3kN/m, respectively. The model examines the effect of tunnel excavation on the settlement of existing buildings. The properties of the soil are presented in Table 2.

Table 2: Soil Layers Parameters (Modified after Broere (2002)

Layer	(1) Fill	(2) Sand	(4) Clay
Soil Model	Hardening soil	Hardening soil	Hardening soil
Depth(m)	(0) to (-4.0)	(-4.0) to (-19.75)	(-23.5) to (-27.5)
γ (kN/m^3)	17.2	20	20
E^{ref}_{50} (MPa)	14	35	12
E^{ref}_{oed} (MPa)	14	35	7
E^{ref}_{ur} (MPa)	42	105	35
Stress power (m)	0.5	0.5	0.9
$C^{/}$ (kPa)	3	0.01	7
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OCR	1	1	1
P_{ref} (kPa)	65	65	65
Dilatancy angle (ψ) [°]	--	5	1

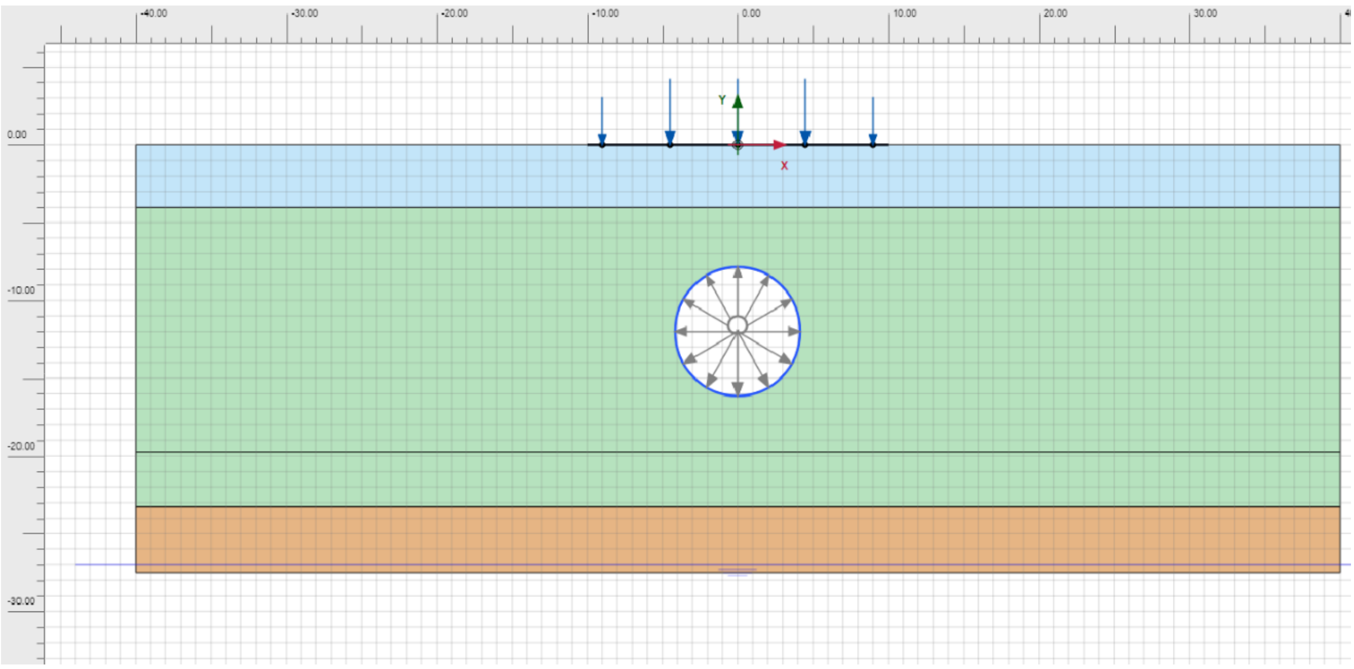

Fig. 3: 2D model Geometry and configuration of Tunnel (Z=7.50 m depth from the ground surface – Tunnel 1)

Figure 4 illustrates the settlement of the raft foundation before and after tunnelling excavation. It indicates that the maximum deformation occurs at the centre of the raft. Before tunnelling, max. Vertical displacement, as per Figure 4, is 6.9mm. After tunnelling, the max. Settlement is 16.2mm.

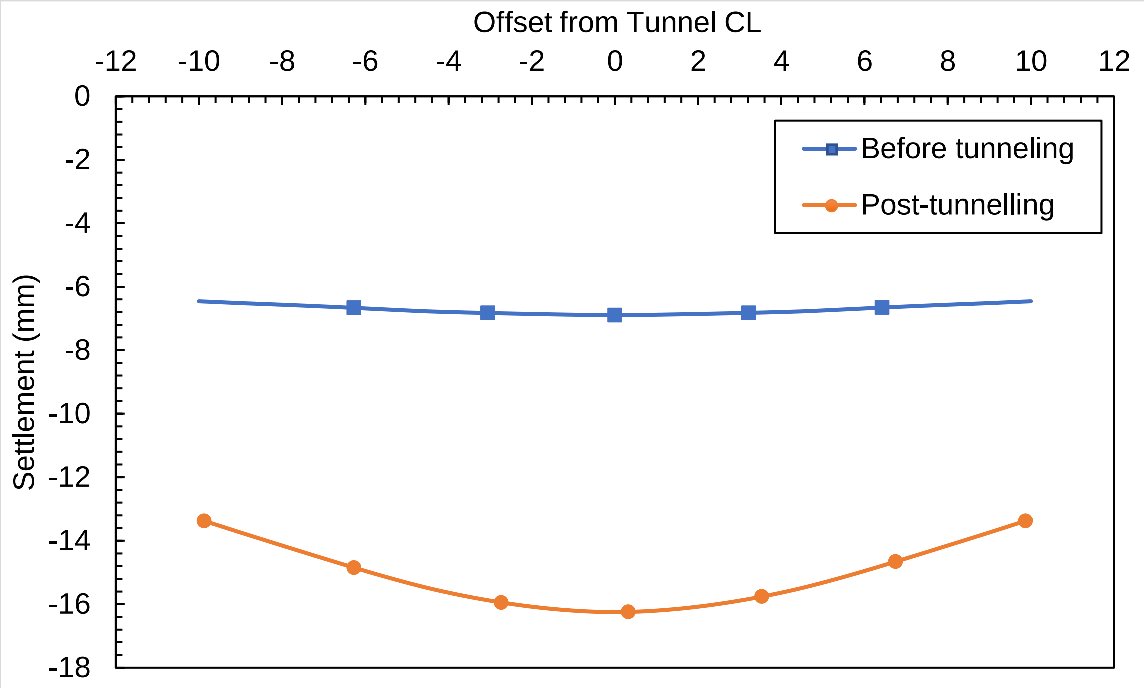

Fig. 4: Settlement of the raft before and after tunnelling.

The effect of tunnels under a raft foundation settlement can lead to additional deformation in the vertical and horizontal directions in the surrounding soil, causing total settlement and potential differential settlement across the foundation. The depth, proximity, and diameter of the tunnels influence the magnitude of the settlement. Thus, the effect of tunnel depth, soil consistency, and the effect of two closely spaced tunnels on the settlement of the raft foundation was examined in the following sections.

3.1. Effect of tunnel depth

The effect of increasing the tunnel depth, on the induced settlement of the raft foundation, has been examined herein. The induced maximum settlement values were 18.2mm, 16.2mm, and 12.4mm for tunnel depths of 10 m, 7.50 m, and 5 m, respectively, as shown in Figure 5. This may be attributed to an increase in the thickness of the cover material. The depth of the tunnel can have a significant potential effect on the total settlement of the raft foundation. Deeper tunnels are more likely to induce larger settlement in the surrounding soil. The excavation process during tunnel construction, along with subsequent settlement. As the depth of the tunnel increases, the magnitude of settlement effects on the raft foundation is likely to be greater.

Surface settlement of the ground surface decreases with the increase in the buried depth of a tunnel. This could be attributed to the arch effect of overburden soil which generated at the top of the tunnel. It is well known that the arching effect helps to transfer loads around the tunnel, further minimizing surface settlements.

Moreover, deeper soil layers or rocks are denser and stronger, offering better resistance to deformation. The zone of influence is more confined at greater depths, reducing the effect on the surface.

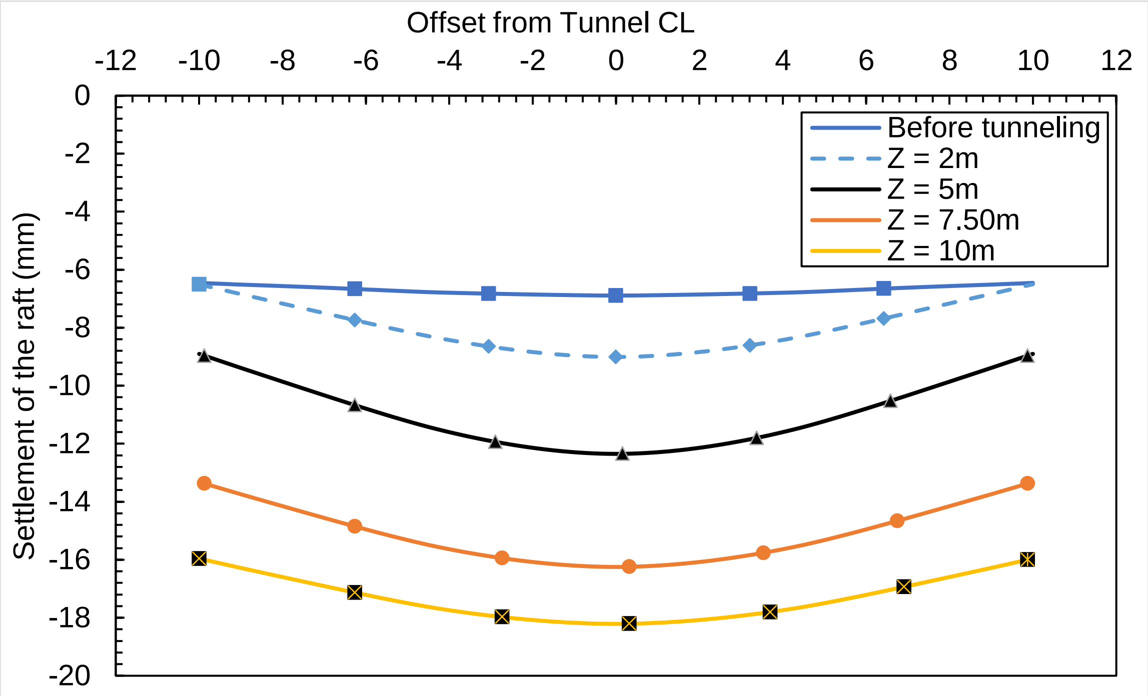

Fig. 5: Settlement of the raft foundation for various tunnel depths.

3.2. Effect of soil consistency

The soil stiffness should affect the total settlement of the raft foundation. Thus, the consistency and stiffness of the sandy soil were changed from loose to very dense. This observation suggests that higher resistance to shear forces in the soil leads to diminished settlement. The findings revealed that increasing the angle of friction from 25 degrees to 40 degrees results in a notable reduction in total settlement from 18.3 mm at 25° to 5.13 mm at 40°, Figure 6. Moreover, as the angle of friction increased from 25 degrees to 40 degrees, the additional total settlement of the raft foundation caused by tunnelling decreased from 8.5 mm to 2.5 mm. This implies that as the soil's ability to withstand shear forces improved, the amount of additional settlement that induced by tunnelling decreased accordingly.

The effect of increasing sand soil stiffness on tunnel settlement has significant implications for tunnel engineering. When the stiffness of the sandy soil is enhanced, it becomes more resistant to deformation and load transmission. As a result, the settlement of the tunnel is reduced. The increased soil stiffness leads to reduced immediate settlement during tunnel construction and long-term consolidation settlement. Moreover, the improved lateral support provided by stiffer soil enhances tunnel stability and reduces the potential for tunnel deformation. The overall impact includes a more uniform settlement distribution, decreased differential settlement, and improved tunnel performance and serviceability. However, careful consideration is necessary to avoid excessively stiff soils, as they may pose challenges during tunnel excavation. An optimal balance in soil stiffness ensures the successful design, construction, and long-term performance of tunnels.

Achieving a balance between minimizing settlement and managing construction challenges in tunnel engineering critically depends on soil stiffness. This balance is essential for ensuring the structural integrity of super-structures and the feasibility of tunnel construction. To achieve this, a multifaceted approach is required, encompassing soil condition evaluation through geotechnical surveys, and testing to determine soil stiffness, optimizing tunnel design to suit soil conditions, selecting appropriate tunneling methods and equipment, employing ground improvement techniques in less ideal soil conditions, and implementing real-time monitoring for adjustments during construction. Additionally, staged construction with careful monitoring and reinforcement can manage soil effects and reduce settlement risks. This comprehensive strategy, combining thorough planning, adaptive design, and continuous monitoring, must be customized to the site's specific conditions to mitigate soil stiffness risks effectively, ensuring structural safety and project success.

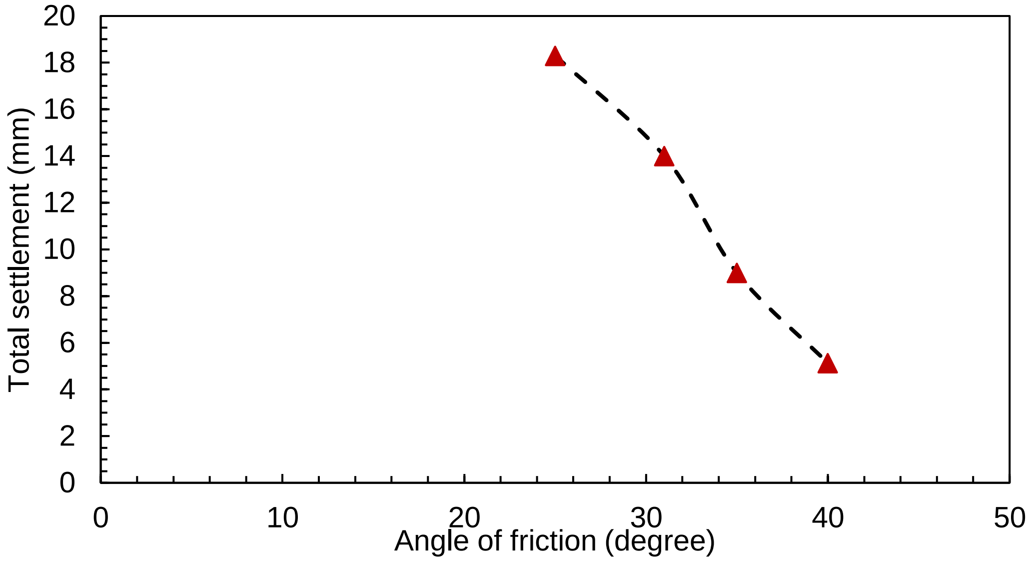

Fig. 6: Effect of soil properties on the total settlement of the tunnel

3.3. Effect of two closely spaced tunnels.

The impact of closely spaced tunnels on the induced vertical displacement of the raft foundation is depicted in Figure 7. The depth of the tunnel influences the bending moment observed between columns as shown in Figure 8. Reducing the tunnel spacing leads to an increase in the maximum vertical displacement. Figure 9 presents shading contours for two closely spaced tunnels with different spacing between them. The tunnelling causes an additional 14 mm settlement in the raft foundation when the tunnels pass beneath it. However, with increasing tunnel spacing, the raft foundations experience less settlement as the tunnels is positioned further away from the centre of the foundation. This leads to a reduction in the total settlement of the tunnels. Consequently, the settlement of the raft foundation decreases significantly, as shown in Figure 7, with total settlement values of 14mm, 12.9mm, 11.96mm, 11.4mm and 10.18mm for Spacing from centre to centre of the two tunnels 1.2D, 1.5D, 2D, and 3D, respectively (where, D = 8.3m, tunnel diameter).

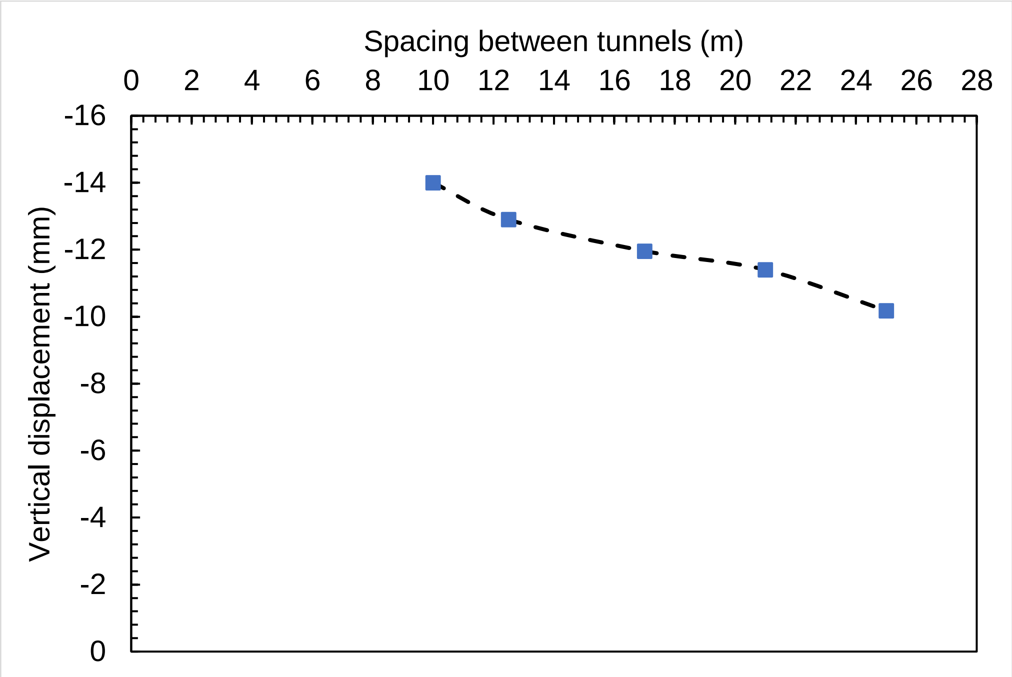

Fig. 7: Settlement of the raft foundation for various tunnel spacing.

Figure 8 shows the raft bending moment for two closely spaced tunnels passed underneath the raft. The diameter of the tunnels is 8.3 m, and the distances between them range from 10 to 25 m ((a) S = 1.2D; (b) S = 1.5D; (c) S =2D; (d) S = 3D).

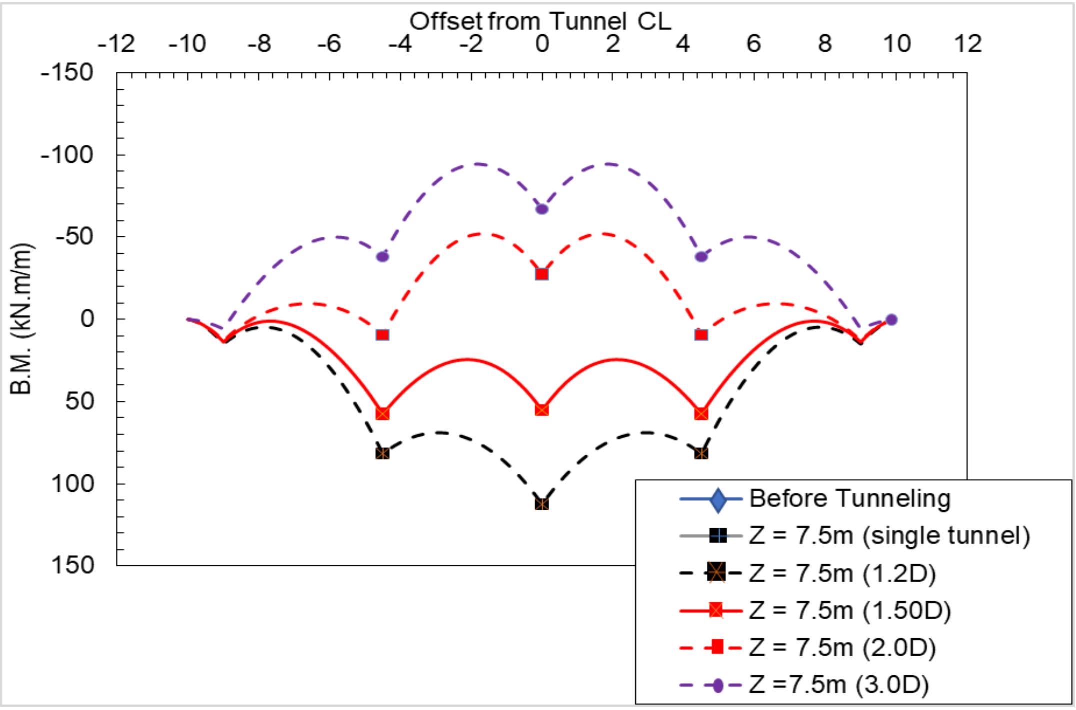

Fig. 8: Induced Bending Moment of the raft foundation for two tunnels with different clearances

Figures 9 (a-d) show the total displacement contours for two closely spaced tunnels passed underneath the raft foundation. The diameter of the tunnels is 8.3 m, and the distances between them range from 10 to 25 m ((a) S = 1.2D; (b) S = 1.5D; (c) S =2D; (d) S = 3D).

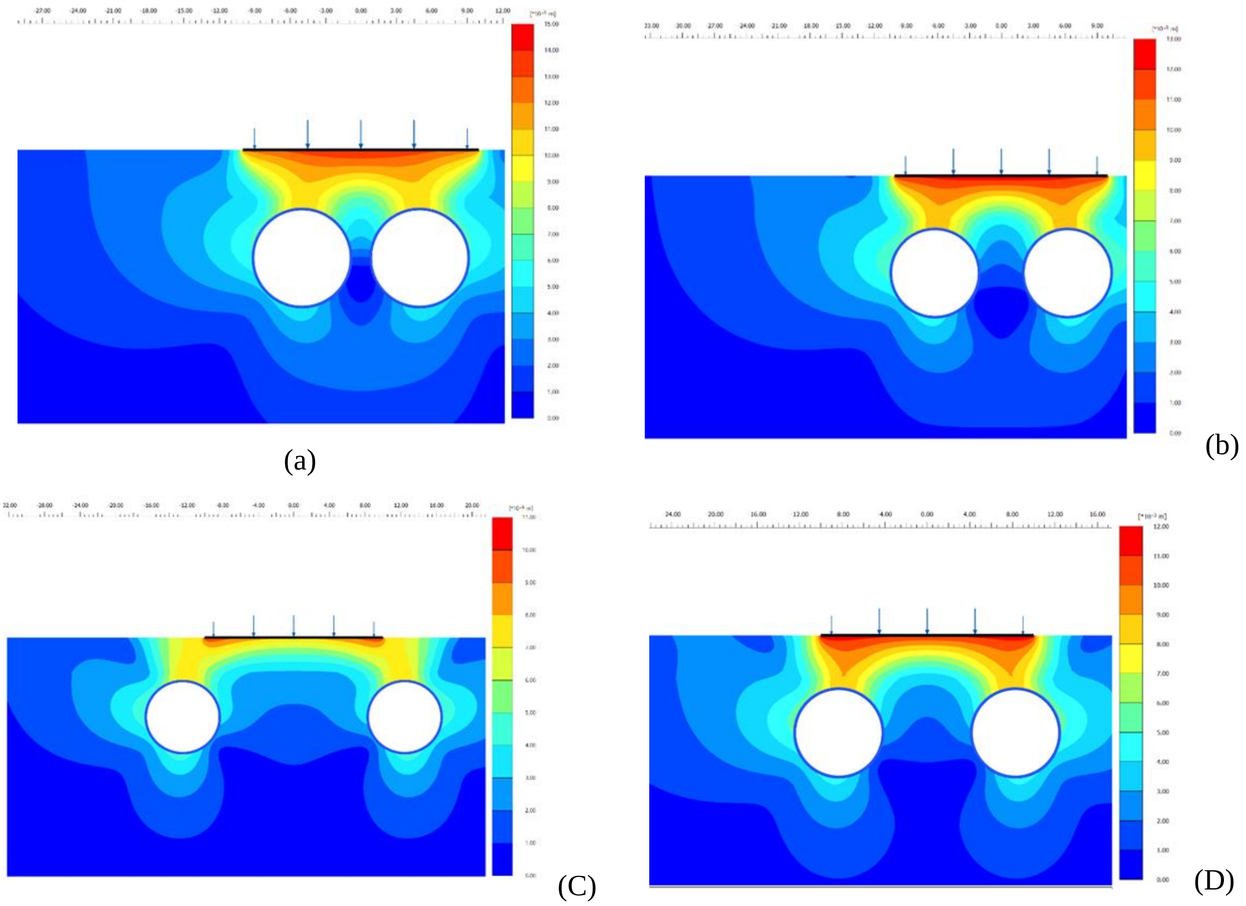

Fig. 9: Contours of the total settlement after the tunneling process in sand soil for two tunnels with spacings of a) 1.2D, b) 1.5D, c) 2D, and d) 3D.

Figure 10 shows the variation of settlement *of the raft after tunneling/ settlement of the raft before tunneling,* along the raft foundation caused by the passage of two closely spaced tunnels and the vertical distance between the raft and the tunnel crest was 7.5m. The study compared these results with the raft experiencing no tunneling and rafts with a single tunnel directly under the raft's centerline. The findings indicate that the displacement at the centre of the raft foundation was substantial when the tunnel spacing was 1.5D and 1.2D (where D represents tunnel diameter). However, as the tunnel spacing increased, the displacement decreased. It is observed that the decrease is significant at the centre of the raft. Furthermore, in all closely spaced tunnel scenarios, the corners of the raft foundation exhibited higher displacement compared to the case with a single tunnel. Additionally, Figure 10 and 11 illustrates that as the spacing between tunnels increased, the differential settlement, between the middle of the foundation and its edge, also decreased. These observations highlight the significant influence of tunnel spacing on the vertical displacement of the soil and the settlement of the raft foundation.

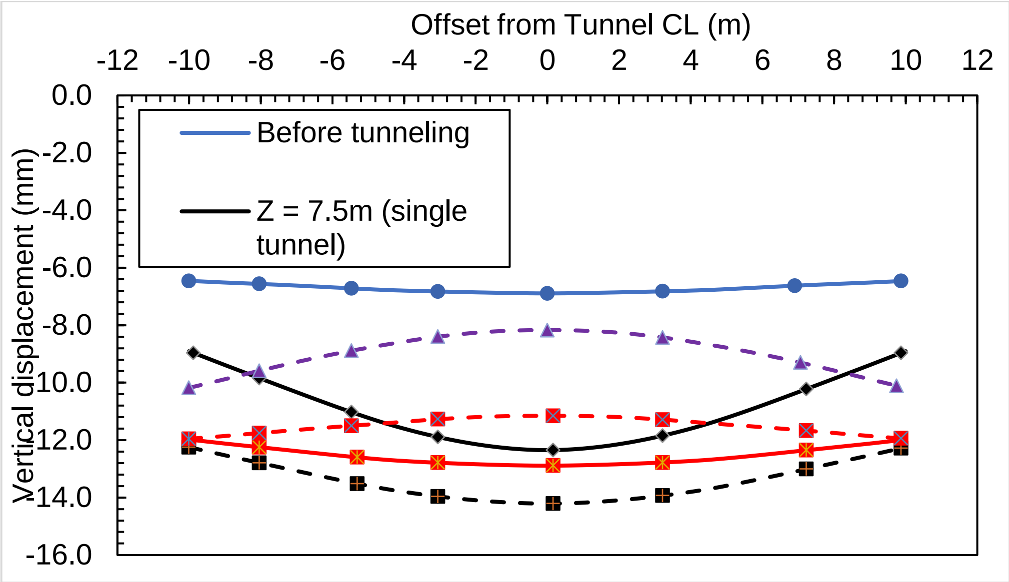

Fig. 10: Vertical displacement of the raft foundation after two closely 8.3m diameter spaced tunnels passes underneath it and the locations of tunnels were 7.5m depth (spacing between tunnels = 1.2D to 3D).

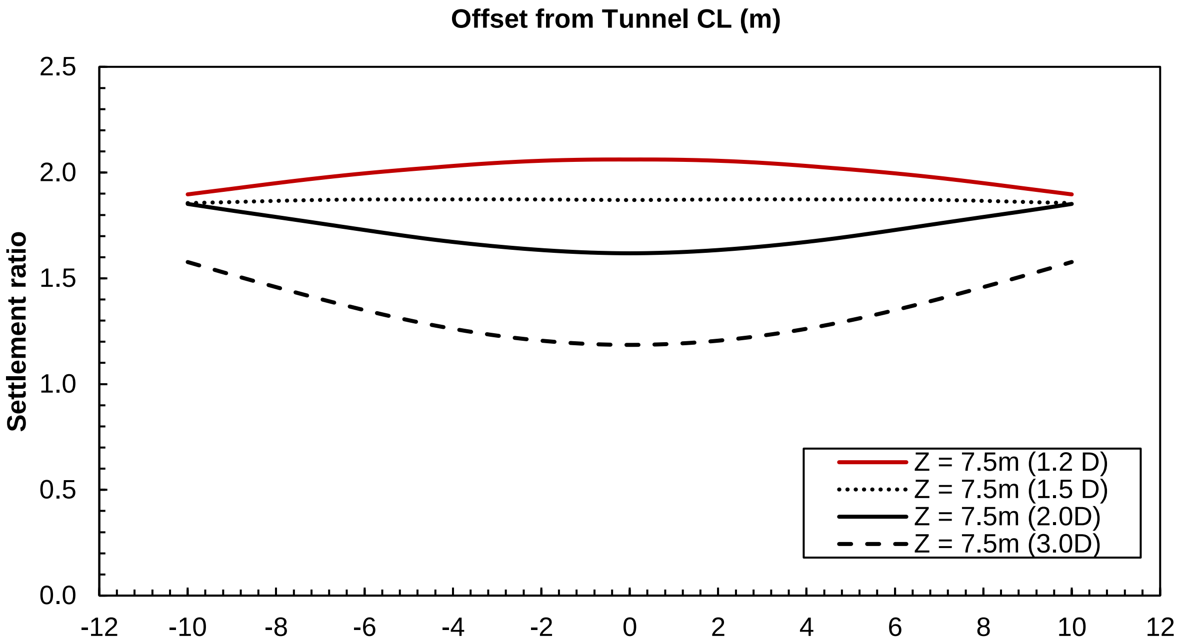

Fig. 11: Variation of settlement ratio along the raft foundation after tunneling (the locations of tunnels were 7.5m depth; spacing between tunnels of 1.2D to 3D).

Increasing the spacing between two tunnels has a substantial effect on the settlement of the raft foundation. When the tunnels are spaced further apart, the settlement experienced by the raft foundation is reduced. This reduction in settlement is attributed to the decreased interaction and influence of the tunnels on the surrounding ground and the foundation. As the tunnels are positioned farther away from the centerline, the load distribution becomes more uniform, resulting in less concentrated settlement beneath the raft. Optimal spacing between closely spaced tunnels is crucial to minimize settlement effects and ensure the stability and long-term performance of the raft foundation. Proper consideration of tunnel spacing during the design phase can mitigate potential settlement-related issues and contribute to the successful implementation of tunnelling projects.

4. Possible Effects of Ignoring TBM Behaviours

Ignoring the behaviors of Tunnel Boring Machines (TBM) during tunnel construction can lead to significant underestimations or misinterpretations of the impact on ground movement and the behavior of resting structures. TBMs play a crucial role in determining the magnitude and distribution of ground displacements and stresses induced by tunneling activities. Their operation influences ground loss, the pressure applied to the tunnel face, the rate of tunnel advance, and the effectiveness of support systems, all of them can have direct and significant effects on the surrounding soil and existing structures. For instance, underestimating ground movements can occur as TBMs cause varying soil disturbances based on their type, soil condition, and tunneling method. Ignoring these factors may lead to inadequate predictions of settlement and lateral displacements. Inaccurate settlement predictions arise from neglecting the rate of tunneling and the pressure at the tunnel face, which significantly affect ground loss and settlements. Without considering TBM behaviors, predictions may not reflect actual conditions accurately. Misjudging structure responses can happen when the complex interaction between tunneling-induced movements and structures is overlooked, potentially misestimating the stress and strain on them. Additionally, the influence on adjacent tunnels may be overlooked in projects with multiple tunnels, where TBM behavior, like sequential operation and relative positioning, significantly affects ground movements and stress distributions.

Future studies should prioritize a thorough analysis of TBM parameters including thrust, torque, cutter head speed, and face pressure to better understand their effects on ground movements and structural behaviors. Developing integrated TBM-soil-structure interaction models will enable a deeper insight into the dynamic effects of tunneling, incorporating both sequential and spatial aspects of TBM operations. Moreover, collecting and analyzing empirical data from diverse TBM types and operations will enhance our understanding of TBM impacts on tunneling outcomes, emphasizing the need for detailed monitoring of ground movements, structural stresses, and the efficacy of support systems. Advanced numerical simulations, such as 3D finite element models, should be leveraged to simulate TBM tunneling processes in detail, including operation modes and excavation sequences. Additionally, exploring various mitigation measures to address the adverse effects of tunneling, through ground improvement techniques, optimization of TBM operational parameters, and structural design modifications, is crucial. By focusing on these recommendations, future research can offer valuable insights and guidelines for tunneling projects, aiming to minimize environmental and structural impacts and ensure the safety and stability of urban infrastructure.

5. Practical Implications

The study's findings have significant practical applications for urban tunnel planning and construction, offering valuable insights for planners and engineers on mitigating the effects of tunneling on ground movement and the behavior of resting structures. By highlighting the critical influence of tunnel depth, soil consistency, and spacing between tunnels on settlement and bending moments, the research provides a foundation for developing guidelines that can enhance the design and execution of tunneling projects. These guidelines may include strategies for optimal tunnel placement, the necessity of comprehensive soil condition assessments, and the importance of considering the cumulative impact of multiple tunnels to minimize adverse effects on nearby structures. Furthermore, the study underscores the importance of real-time monitoring and adaptive construction techniques to address dynamic ground conditions, ensuring the safety and stability of urban infrastructure. Planners and engineers can apply these insights to improve the resilience of buildings and infrastructure, reduce the risk of damage, and ensure that urban tunneling projects are executed with minimal disruption to the built environment.

6. Conclusions

This study has provided significant insights into the effects of tunneling on ground movement and the structural integrity of resting structures, particularly raft foundations, within urban environments. Through the employment of a 2D finite element model and the validation of tunnel modeling with field data, this research has highlighted the substantial impact of several factors such as tunnel depth, soil consistency, and the spacing between tunnels on settlement patterns and bending moments. The findings demonstrate the critical importance of careful tunnel placement and soil cover management, with raft settlement increasing significantly when tunnels are directly below shallow depths and bending moments escalating with reduced soil cover thickness above tunnels. The primary conclusions drawn from this study are as follows:

1. After the tunnel advancement process underneath the raft foundation, the raft maximum settlement tended to increase, regardless of the soil relative density, and attained more than 250% of its final value when the tunnel was located directly beneath the raft centerline at 7.5 m depth.
2. The increase in the soil cover above the tunnel crown (Z), led to an increase in the bending moment of the raft. The raft bending moment due to the tunnelling process has been observed to a cover thickness of 10 m. At the shallowest depth Z = 2 m, the raft bending moment was higher than the initial case before the tunnelling construction began by 30% for sand. Increasing Z up to 5, the raft was observed to suffer additional bending moments due to the tunnelling process. The raft bending moment increased up to 400%, and 300% covering depths of 5 m and 7.5 m, respectively.

3. The maximum total settlement values at the final stage of the tunnel construction process decrease as the density of the soil increases.
4. For the two close tunnels, the spacing of 1.2 diameter shows the high impact on the vertical settlement of the raft. Increasing the spacing by more than 1.2D causes a reduction in the total settlement of the raft. Similarly, the bending moment with the highest spacing between tunnels of 1.2D decreased with an increase in the spacing between tunnels.

Nomenclature

- TBM (Tunnel Boring Machine): A machine used for excavating tunnels with a circular cross-section through a variety of soil and rock strata.
- Raft Foundation: A type of foundation that spreads the load from a structure over a large area, usually used where soil conditions are poor.
- Ground Movement: Displacement of the ground surface and subsurface layers due to various factors, including tunneling activities.
- Settlement: Vertical displacement or sinking of the ground or a structure's foundation due to the weight of the structure or other changes in ground conditions.
- Bending Moment: The internal moment that induces bending stress within a beam or slab foundation, reflecting the structural response to external loads or ground movements.
- Soil Density: A measure of soil compaction, often categorized as loose, medium dense, dense, and very dense, affecting soil strength and deformation characteristics.
- Tunnel Depth (Z): The vertical distance from the ground surface to the top of the tunnel.
- Soil Cover: The thickness of soil above the tunnel crown.
- Tunnel Spacing (TS): The distance between adjacent tunnels, influences the interaction and cumulative effects on ground and structure behavior.
- Diameter of Tunnel (D): The cross-sectional width of the tunnel, is critical for assessing the scale of tunneling operations and their impacts.
- Finite Element Model (FEM): A computational technique used to simulate and analyze physical phenomena, applied here to model the interactions between tunneling activities and structural foundations.
- PLAXIS: A computational software used for the analysis of deformation and stability in geotechnical engineering and soil mechanics.

References

[1] Ding, Z., Ji, X., Li, X., & Wen, J. (2019). Numerical investigation of 3D deformations of existing buildings induced by tunneling. Geotechnical and Geological Engineering, 37, 2611–2623.

[2] Docklands Light Railway Lewisham Extension – East London. Soils Found. 39(3), 99–112 (1999)

[3] Mroueh, H., & Shahrour, I. (2003). A full 3-D finite element analysis of tunneling--adjacent structures interaction. Computers and Geotechnics, 30(3), 245–253.

[4] Rajabi, A. M., Mahmoudi, M., & Taebi, M. (2021). A numerical study of the effect of tunneling on surface settlement and existing buildings. International Journal of Engineering, 34(5), 1085–1093.
[5] Shahin, H. M., Nakai, T., Ishii, K., Iwata, T., & Kuroi, S. (2016). Investigation of the influence of tunneling on existing building and tunnel: model tests and numerical simulations. Acta Geotechnica, 11, 679–692.
[6] Wu, H., Gan, X., Liu, N., Yang, K., & Sun, Z. (2024). Analysis of tunneling-induced ground movements in spatially variable soil under the influence of existing building. Computers and Geotechnics, 166, 106003.
[7] Maleki, M.: An equivalent beam model for the analysis of tunnel-building interaction. Elsevier Ltd (2011). doi: 10.1016/j.tust.2011.02.006
[8]Moller, S.: Tunnel-induced settlements and structural forces in the lining. Ph.D. thesis, Institute of Geotechnical Engineering, University of Stuttgart (2006)
[9] O'Reilly, M.P., New, B.M.: Settlements above tunnels in the United Kingdom: their magnitude and prediction. In: Proceedings of the Tunneling 1982, Brighton, pp. 173–181 (1982)
[10] Indra. N. H., (2021): 2D vs. 3D Numerical Modelling of NATM Tunnel using Finite Element Method. Pengajuan Hak Kekayaan Intelektual
[11] Peck, R.B.: Deep excavation and tunneling in soft ground. In: Proceedings of 7th International Conference on Soil Mechanic Foundation Engineering, Mexico, State-of-the-Art Volume, pp. 225–290 (1969).
[12] PLAXIS 2D (2022), Material models manual.
[13] Schädlich, B., & Schweiger, H. (2014b). Internal report shotcrete model: Implementation validation and application of the shotcrete model. Delft: Plaxis
[14] Sugiyama, T., Hagiwara, T., Nomoto, T., Nomoto, M., Ano, Y., Mair, R.J., Bolton, M.D., Soga, K.: Observations of ground movements during tunnel construction by slurry shield method at the