Journal of Rock Mechanics and Tunnelling Technology (JRMTT)
30(2) 2024 pp 83-99

Available online at www.isrmtt.com

Study of Pile Behaviour during Tunnel Construction in the Vicinity with Changing Tunnel and Pile Diameter

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ABSTRACT

Modern urban development often requires the construction of tunnels, which can have a significant impact on existing structures like raft or pile foundations, as well as the surrounding substructures. This research aims to provide a comprehensive understanding of the complex interactions that occur among tunnels, piles, and adjacent soil (TPS). Employing numerical techniques, the study utilizes the PLAXIS3D finite element software to delve into the intricacies of Tunnel-Pile-Soil Interaction (TPSI). Specifically, this investigation focuses on evaluating how tunnel excavation affects 2×2 pile groups. Through a systematic analysis of various parameters, the study uncovers that changes in tunnel diameter and pile diameter play a substantial role in influencing deformation patterns and bending moments within this system.

Keywords: Tunnel; Pile; Soil-structure interaction; Pile response; Tunnel diameter; Pile diameter.

1. INTRODUCTION

1.1 General

Tunnelling in urban areas introduces a spectrum of risks to surrounding structures, ranging from minor issues like inner wall cracks to more severe concerns such as service pipe fractures and structural instability. These risks not only jeopardize the serviceability of existing structures but also challenge the adherence to ultimate limit state requirements. In response to these challenges, engineers seek effective solutions to comprehensively evaluate the impact of tunnelling-induced ground movements, especially in soft soil conditions. Tunnels serve as critical infrastructure components for various urban applications, including metro systems, transportation networks, water supply, sewerage systems, and telecommunications. A fundamental aspect of this assessment is the complex problem involving Tunnel-Pile-Soil Interaction (TPSI), where a consistent deformation pattern can be seen around the tunnel which arises from the interplay between horizontal and vertical soil movements. As highlighted by Pang et al. (2006), the satisfactory performance of a tunnel depends upon the below-mentioned three key criteria.

- Safely constructing the tunnel while ensuring its advancement without any undue risks.
- Minimizing the disruption during construction and preventing the damage that may affect the safety of adjacent or overlying structures which include utilities, buildings, streets, etc.

- Ability to withstand external forces throughout its operational lifespan.

Keeping these crucial criteria in mind, the current research pens down the problem involving complex dynamics of tunnel-pile-soil interaction (TPSI), aiming to address the multifaceted challenges posed by tunnelling in urban environments.

1.2 Literature Review

The seminal work in the field of tunnelling is pioneered by many researchers such as Lee et al. (1994), who have conducted a study on vertical pile movements in the vicinity of an underground station in London which shows that the piles behave like columns in response to tunnelling activities. Similar studies done by Loganathan and Poulos (1998) are considered of very high importance, which laid the foundation for subsequent research in this area. Loganathan et al. (2001) and Loganathan & Poulos (1998) emphasized the potential threat posed to structures with pile foundations due to ground movements induced by tunnelling activities. Further, the pile behaviour with respect to tunnel advancement is explored by many other researchers which includes Kaalberg et al. (2005), Pang et al. (2006), and Selemetas and Standing (2017).

Building upon these foundational studies, Ahmed and Iskander (2011) have proposed a transparent soil model to investigate soil deformation and settlement profiles near tunnels. Centrifuge testing by Ng et al. (2013 & 2014) yielded insights into axial forces experienced by single and grouped piles during tunnelling in physical modelling tests. Results revealed that twin tunnel construction near the mid-depth of a pile led to increased axial forces compared to locations near the pile toe or below it. In similar studies conducted by the same researchers regarding pile head settlement before and during tunnel excavation, the additional settlement induced by tunnelling is discussed briefly. Their investigations also delved into the impact of twin tunnels on pile capacity considering, tunnel locations near the middle of the pile, at the pile toe level and below the pile toe level. Notably, tunnels excavated below the pile toe level exhibited the most significant loss in pile capacity as reported by Feng et al. (2002), Jacobsz et al. (2004), Ong et al. (2005) and Ng et al. (2015).

Mair and Williamson (2014) highlighted the significant impact of axial forces on piles under various working loads. Piles without working loads exhibited both negative and positive axial forces when tunnels were in close proximity to the pile head. Bending moments along the pile were identified as another critical parameter influenced by tunnel excavation, with Korff et al. (2016) revealing that both negative and positive bending moments occurred, depending on tunnel depth.

Many researchers have taken the help of numerical modelling in solving the problems related to the influence of stimulus generated by external impacts such as the ageing effect reported by Wang et al. (2022), blasting studied by Anas et al. (2021a and 2021b), Anas and Alam (2022) and various others. Among the above detailed numerical analysis, some of the researchers have also proposed numerical models in the same area of research i.e., tunnelling. In the realm of numerical methods, the finite difference method (FDM) was employed by researchers such as Mroueh and Shahrour (2002 & 2003), Tang et al. (2000), Lee and Ng (2005), Lee (2013) and Lee & Jacobsz (2006). Additionally, a combination of the finite element method (FEM) and the boundary element method (BEM) was used in the second step of analysis, as demonstrated by Surjadinata et al. (2006). The same type of study has been done by Zidan and Ramadan (2015, 2016 and 2018), where the nearby pile behaviour affected by tunnelling is studied using three-dimensional finite element analysis. Their study gives a detailed insight regarding the safety aspect of influenced structure due to nearby tunnelling activity which is caused due to unstable ground movements. This comprehensive body of research forms the basis for understanding the complex dynamics of tunnel-pile-soil interactions, while contributing significantly to the field of geotechnical.

2. INVESTIGATION, DATA GENERATION AND ANALYSIS

To gain a comprehensive understanding of how piles respond to tunnel-induced ground movements, a parametric study was conducted to investigate various influential factors affecting pile performance. This study focused on the hypothetical tunnel-pile-soil interaction (TPSI) problem by systematically varying the influencing factors independently, to evaluate their impact on pile deformation.

For this research, PLAXIS-3D is employed (finite element analysis software) for modelling and analysing piles under variable parameters. The soil material used in the model is assumed to be silty clay and modelled based on the Mohr-Coulomb criterion. The pile used in the model is elastic and modelled as an embedded beam element. Pile cap considered as elastic plate element. TBM method is used for modelling, TBM and lining of TBM modelled as a plate in elastic medium. The analysis involved a 2×2 group of circular piles, fixed through a pile cap having dimension as 4.2×4.2 ×1.2 m and length of the pile was 25 m with diameter of 0.9 m as shown in Table 1 and Table 2. A circular tunnel of 9 m dia., containing a 250 mm thick concrete lining is assumed for the current numerical analysis.

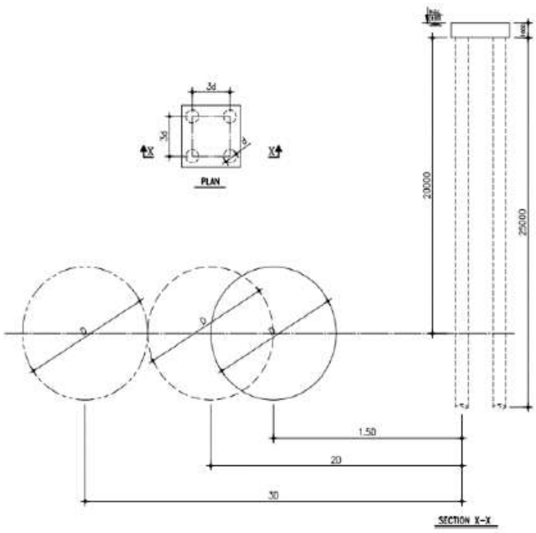
Table 1 - Material properties (Kitiyodom et al., 2005)

Part	Material	Unit Weight γ, (kN/m^3)	Poisson's Ratio, υ	Thickness t (m)	Youngs's Modulus, E (N/mm^2)
Soil	Silty Clay	20	0.5	-	24
Pile Cap	Concrete	25	0.25	1.2	27386
Pile	Concrete	25	0.25	-	27386
Lining	Concrete	25	0.25	0.25	31622

Table 2 - Parameters used in the model

Parameters	Notations	Units	Variations
Diameter of tunnel	D	m	6.75, 9, 13.5
Pile Diameter	d	m	0.6, 0.9, 1.2
Position of tunnel longitudinal axis	z	m	-20, -25
Horizontal Distance between the tunnel centre and centre of near pile	x	m	-15
Pile length	L	m	25

The work methodology of the current numerical analysis involves the gradual change in lateral distance of the tunnel and centre of extreme cornered pile and the shifting of pile group vertically at the same time. The horizontal position of the tunnel is varied with respect to the centre of the pile by the value of 1D, 1.5D, 2D and 3D, where D is the diameter tunnel. At the same time, the vertical position of the tunnel is adjusted from 15 m to 20 m below the ground surface. The analysis encompasses different tunnelling positions in relation to the pile. When the tunnel is positioned above the pile tip, it is referred to as "above the toe". If the tunnel was located at the pile tip, it was designated as "at the toe". Lastly, when the tunnel was situated below the pile tip, it was labelled as "below the toe." These varying scenarios allowed for a comprehensive exploration of pile responses under different conditions of tunnelling-induced ground movements. The same is presented in Figs. 1 and 2 for visual representations of the experimental setup. An existing 2×2 pile group with pile length of 25 m from the NGL is considered for the analysis. Also, the stagewise construction of the tunnel advancing in "y" direction is represented in Fig. 3.



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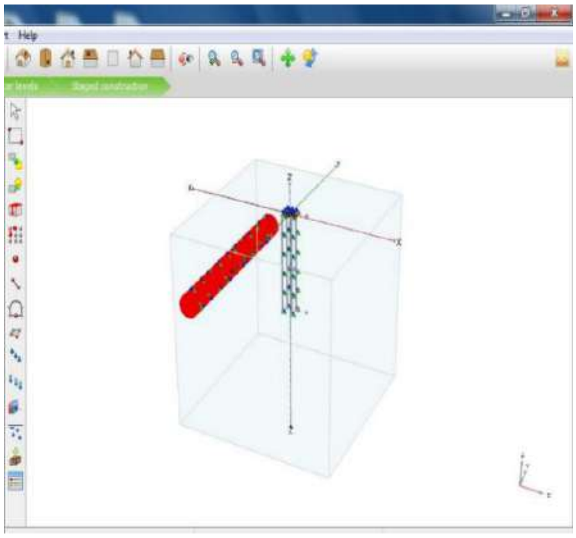


Figure 2 - Image of the proposed model from PLAXIS3D

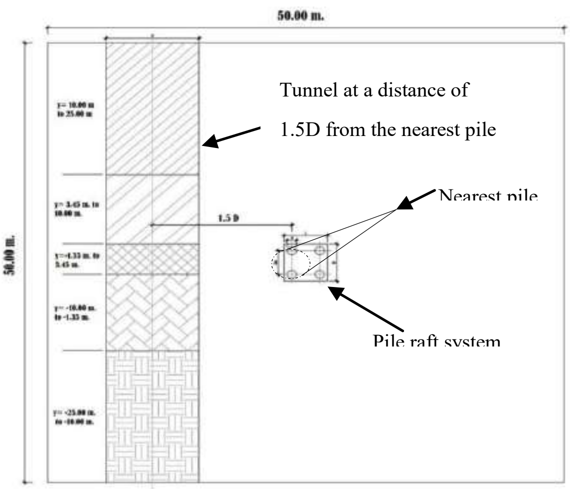


Figure 3 - Sample representation of tunnel advancement

The properties of soil and the piles obtained from the previous studies done by Kitiyodom et al. (2005) are taken. Medium-sized meshing is used with 15 nodded triangular elements which gives more accuracy. To model soil structural interaction positive/negative interfaces and modelled for plate elements. Boundary conditions are considered as the bottom fully fixed, left and right of the domain as normally fixed and top as free. A reduction factor of 0.8 is used for reducing strength and stiffness at interfaces as suggested by Brinkgreve et al. (2011). It is recognized that stage of tunnelling (length of excavated soil and its relative position with respect to the foundation) has important effect on pile foundation response. Nevertheless, most of the results are presented without specific determination of excavated length. It is plane strain model. It considers automatically per m in out-of-plane direction. Analysis done as undrained analysis. Construction stages will include the existing/construction of piles then tunnel construction. The modelling stage follows the pattern of existing/construction of piles then tunnel with help of TBM followed by conicity, tail grouting then lining installation. The steps involved in the current numerical analysis are given below.

- Modelling of soil, pile & pile cap on PLAXIS-3D.
- Analyse the pile response while varying the tunnel vertically.
- All the results are analysed for different tunnel diameters given
  - (i) above the toe.
  - (ii) at the toe.
  - (iii) below the toe.
- All the analysis steps shall be for the following conditions.
- The positional effect of new tunnel on the existing pile foundation is determined in terms of deformations and bending moments of existing pile foundation.

2.1. Response of an Existing Piled Raft Foundation to Tunnelling-Induced Ground Movements

Bending Moments and lateral deflections of the piles during tunnel advancement are analysed. Some of the new terminologies are used in the study to describe the specific condition of the model. Such as the pile closer to the tunnel is termed the “Near” pile and the pile further away from the tunnel is termed the “Rear” pile.

Figure 4a shows the computed lateral deflection profiles of the near pile in the piled raft foundation with respect to the tunnel at variable distances laterally. It can be seen that when the tunnel face is approaching the pile-raft foundation i.e., from the co-ordinates, y = -25.00 m to -10.00 m in model, there is only a slight translation of the pile. When the tunnel face reaches the centre of 1st near pile (i.e., from, y = -10.00 m to -1.35 m), there is a significant amount of lateral deflection of the pile. When the tunnel face just passes the piled raft, (i.e., from, y = -1.35 m to 3.45 m) the pile deflection further increases as obvious by seeing the pattern in the figure. When the tunnel face is further away (y = 3.45 m to 10 m) from the piled raft, the pile deflection increases slightly more. The maximum lateral deflection is observed at the location of the tunnel longitudinal axis (y = 10.00 m to 25.00 m). The pattern of pile deflection profile from y = −25.00 m to 25.00 m. is similar. The deflection profiles. A similar observation has been reported by Chen et al. (1999, 2000, and 2004). Figure 4b shows how the percentage lateral deflection increases with an increase in tunnel advancement with respect to the initial stage (y = -25.00).

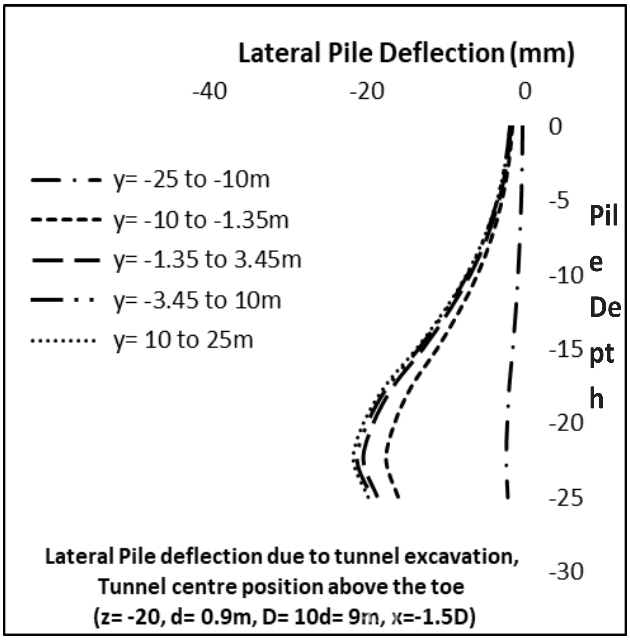


Figure 4a - Lateral deflection profile of the piles at different stages of tunnelling

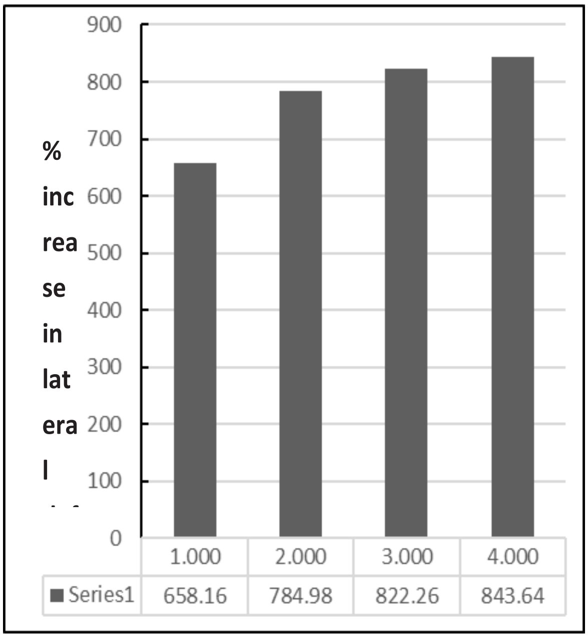


Figure 4b - Pile lateral deflection caused by tunnel advancement relative to the initial tunnelling stage

Figure 5a shows the computed bending-moment profiles of the "Near" pile in the piled raft foundation adjacent to the tunnel at different stages of tunnel advancement. When the tunnel face is approaching the piled raft, the generated bending moments of the pile are very insignificant (y = −25.00 m to -10.00 m). Although, there is a significant amount of bending moments generated in the pile when the tunnel face reaches the centre of 1st "Near" pile (y = -10.00 m to -1.35 m.), (y = -1.35 m.). In a similar manner, as soon as the tunnel approaches nearer to the pile soil interface zone, i.e., when the tunnel face just passes the piled raft, (y = -1.35 m to 3.45 m) the bending moment further increases (y = 3.45 m) and when the tunnel face is further away (y = 3.45 m to 10 m) from the piled raft, the pile bending moments increases slightly more. The maximum bending The pattern of the bending moment profile from y = -25.00 m to 25.00 m is similar.
The deflection profiles and trends are in agreement with Mroueh and Shahrour (2002). Figure 5b shows how bending moments percentage increases with tunnel advancement with respect to the initial stage (y = -25.00).

3. ANALYSIS OF RESULTS AND THEIR COMPARISON WITH THE PREVIOUS STUDY (GOKULDAS ET AL., 2020)

The results obtained are compared with those from ABACUS 3D as reported by Gokuldas et al. (2020). This comparative analysis aimed to explore the impact of tunnelling on the pile group.

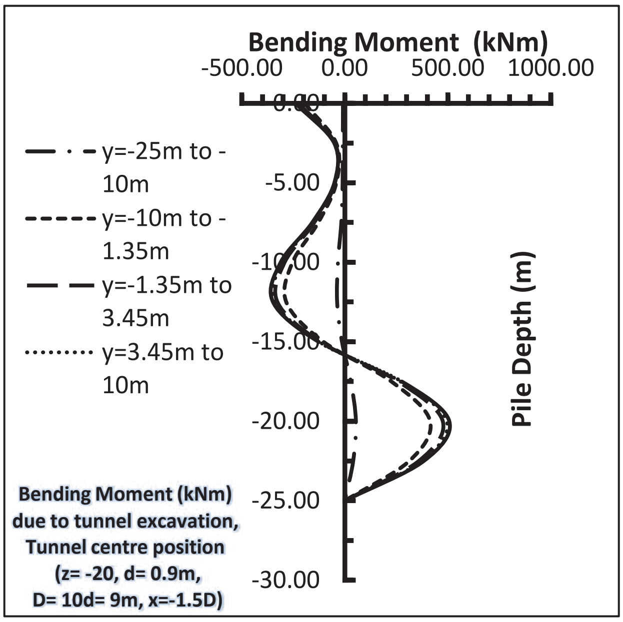


Figure 5a - Bending moments profile of pile at various stages of tunnelling

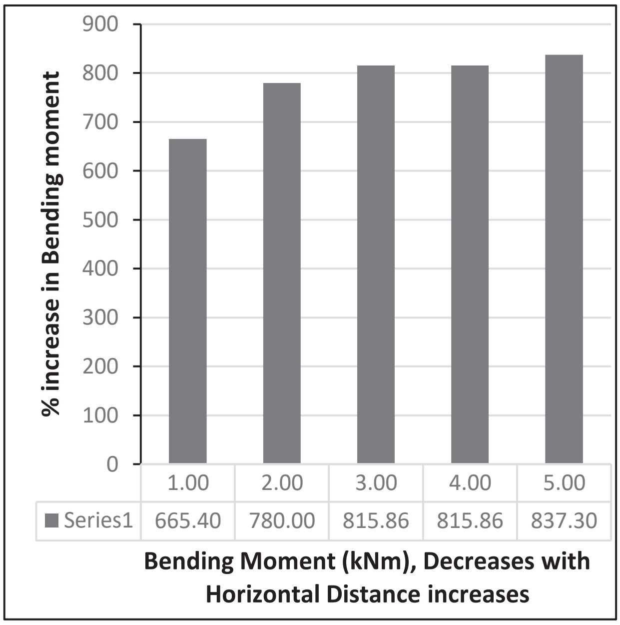


Figure 5b - Percentage increase in bending moments resulting from tunnel advancement in comparison to the initial tunnelling stage

Figure 6a shows the comparison of lateral deflection of current study with previously done by Gokuldas et al. (2020). The current result is found in good agreement with the previously done studies. Figure 6b presents the comparison of bending moment profiles caused by tunnelling in the current study and Gokuldas' earlier work. In this case as well, the present bending moment profile demonstrated a favourable agreement with the previous study's results.

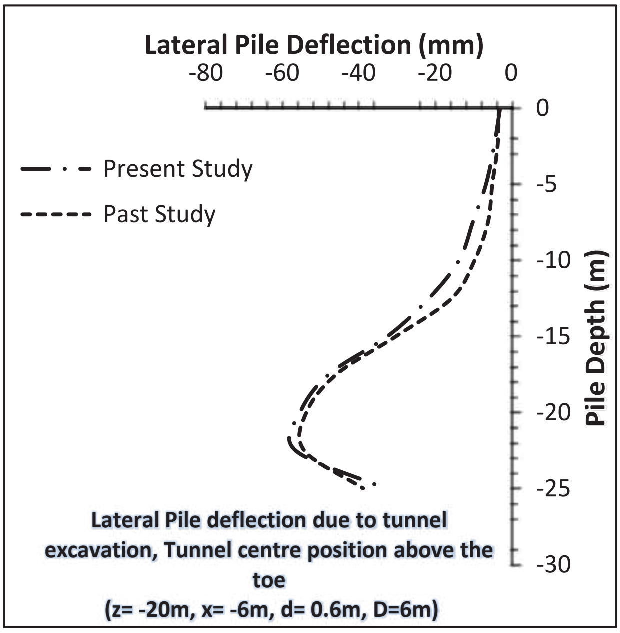


Figure 6a) Pile lateral deformation profiles resulting from tunnelling in the current study and a previous investigation

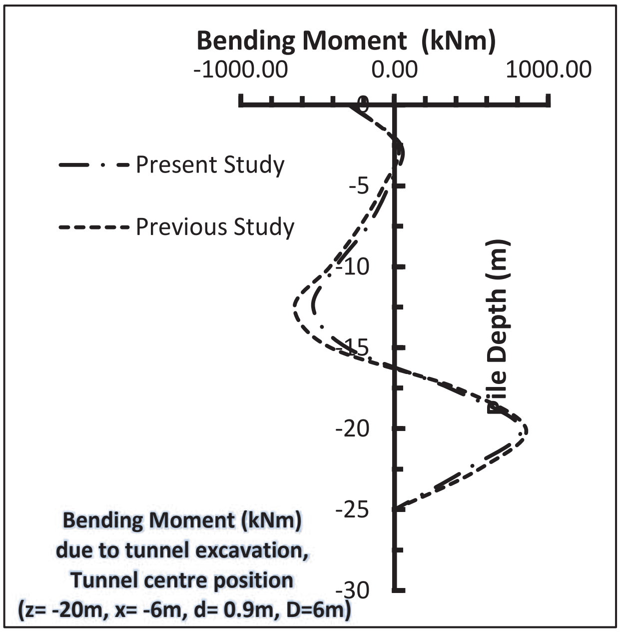


Figure 6b) Comparison of bending moment profiles induced by tunnelling between the current research and the earlier study

4. RESULTS AND DISCUSSIONS

4.1 Pile Lateral Deflection

The tunnel-pile interaction problem is influenced by various factors, including the position of the pile tip, variations in tunnel diameter (D), changes in pile diameter (d), shifts in horizontal distance (x), and variations in soil stiffness (Es), among others. This study specifically examines the impact of the horizontal tunnel position on the nearest pile as obvious because the nearest pile will get affected the most. Figure 7a and Fig. 8a illustrate the changes in lateral deflection in response to variations in tunnel diameter. This comprehensive analysis aimed to assess the influence of varying tunnel diameters on lateral deflection. The analysis encompassed two distinct scenarios: the first scenario involved the tunnel positioned at (z = -20m, x= -15m) with a pile diameter of 0.9 m, the second scenario varying the vertical position of tunnel (z= -25m, x= -15m) with an identical pile diameter of 0.9 m. In both cases, tunnelling was conducted with diameters of 6.75m, 9m, and 13.5m, corresponding to 7.5 times, 10 times, and 15 times the pile diameter (D= 7.5d, 10d, and 15d, respectively). The study specifically investigated lateral displacements of the pile at depths of -20m and -25m for tunnel diameters of (D= 7.5d, 10d, and 15d), while keeping the vertical position of the tunnel fixed at -20m and -25m. Figure 9a and Fig. 10a depicts the variations in lateral deflection in response to changes in pile diameter. This comprehensive analysis was conducted to evaluate the impact of varying pile diameters on lateral deflection. The study considered two specific scenarios: the first scenario placed the tunnel at (z = -20m, x = -15m) with a tunnel diameter of 9m, while the second scenario adjusted the vertical position of the tunnel to (z= -25m, x= -15m) while maintaining the same tunnel diameter of 9m. In both cases, pile diameters of 0.6m, 0.9m, and 1.2m (d= 0.6d, 0.9d, and 1.2d) were examined. The research specifically focused on analysing the lateral displacements of the pile at depths of -20m and -25m for pile diameters of, D_p= 0.6d, 0.9d, and 1.2d), while keeping the vertical position of the tunnel constant at -20m and -25m.

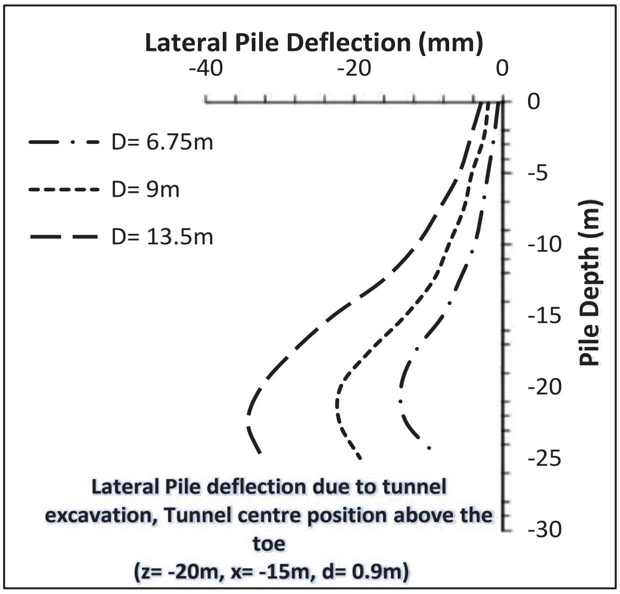


Figure 7a - Pile lateral deflection with varying diameter of tunnel (z= -20m)

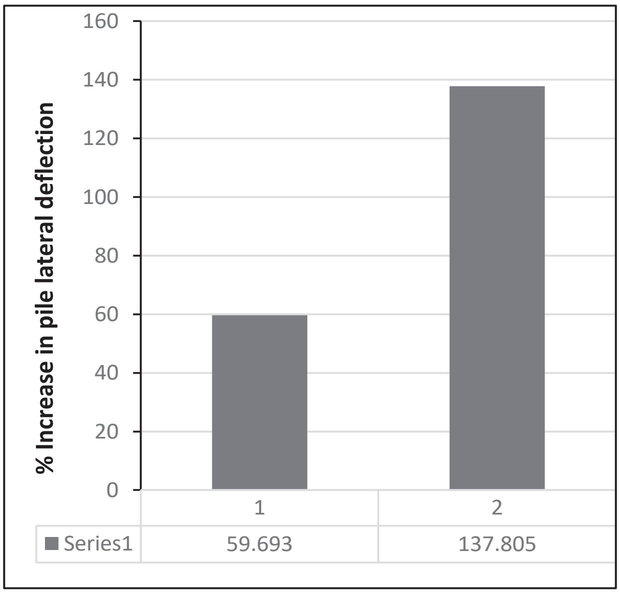


Figure 7b - Percentage increase in pile lateral deflection as the diameter of tunnel increases (20m)

In the context of pile lateral deflection at a depth of -20m with varying tunnel diameters, Fig. 7b shows notable fluctuations. Particularly, when the tunnel diameter reached 9m (equivalent to 10 times the pile diameter, D = 9m or 10d), the lateral deflection exhibited a 60% increase compared to the situation when the tunnel diameter was 6.75m (equivalent to 7.5 times the pile diameter, D = 6.75m or 7.5d). Furthermore, under the conditions of D = 9m or 10d, the lateral deflection experienced a substantial 137% increase in comparison to the scenario with D = 6.75m or 7.5d. In the context of pile lateral deflection at a depth of -25m with varying tunnel diameters, Fig. 8b shows notable fluctuations. Particularly, when the tunnel diameter reached 9m (equivalent to 10 times the pile diameter, D = 9m or 10d), the lateral deflec tion exhibited a 59% increase compared to the situation when the tunnel diameter was 6.75m (equivalent to 7.5 times the pile diameter, D = 6.75m or 7.5d). Furthermore, under the conditions of D = 9m or 10d, the lateral deflection experienced a substantial 152% increase in comparison to the scenario with D = 6.75m or 7.5d.

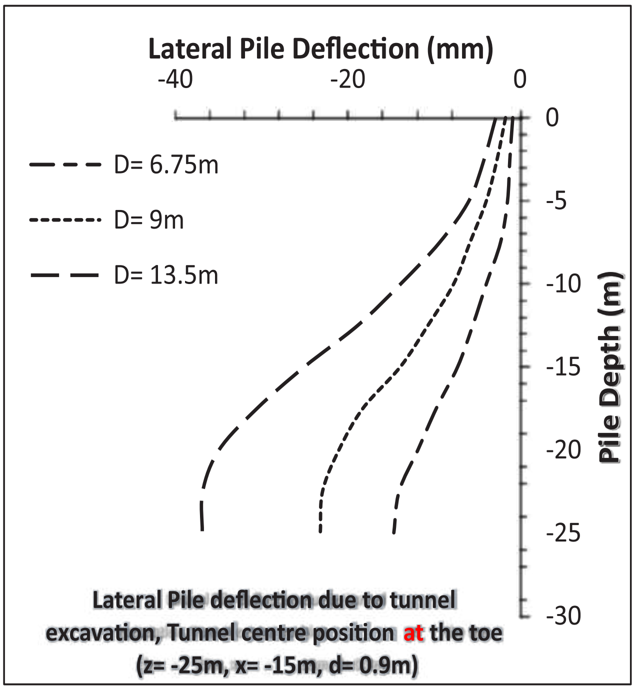


Figure 8a - Pile lateral deflection with varying diameter of tunnel (z= -25m)

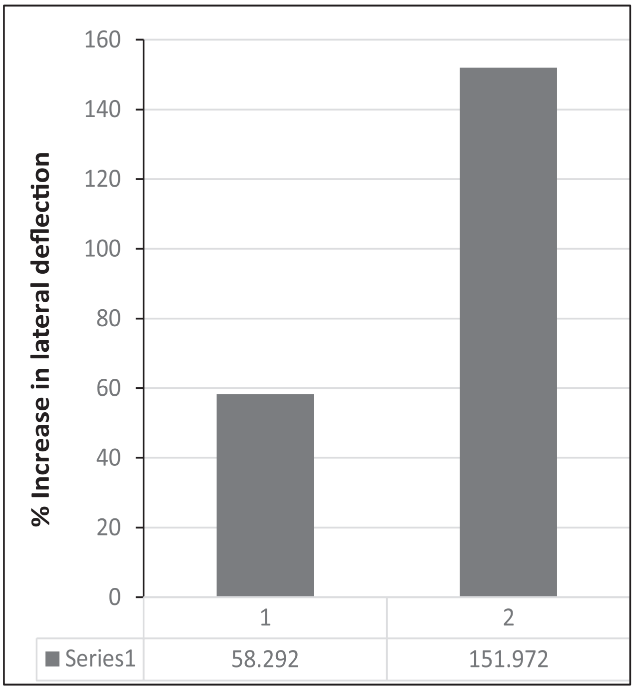


Figure 8b - Percentage increase in pile lateral deflection as the diameter of tunnel increases (z = -25m)

Regarding the lateral deflection of the pile at a depth of -20m with varying tunnel diameters, Fig. 9b displays significant variations. Specifically, when the pile diameter was 0.9m, the lateral deflection decreased by 13% in contrast to the scenario with a 0.6m pile diameter. Moreover, the lateral deflection experienced a substantial 33% reduction compared to the situation with a 0.6m pile diameter. Regarding the lateral deflection of the pile at a depth of -25m with varying tunnel diameters, Figs. 10a and 10b displays significant variations. Specifically, when the pile diameter was 0.9m, the lateral deflection decreased by 12.5 % in contrast to the scenario with a 0.6m pile diameter. Moreover, the lateral deflection experienced a substantial 32 % reduction compared to the situation with a 0.6m pile diameter.

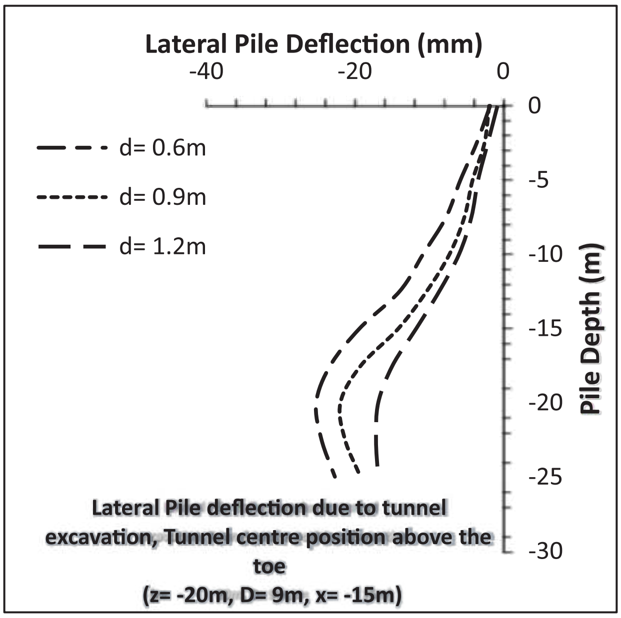


Figure 9a - Pile lateral deflection with varying pile diameter (z= -20m)

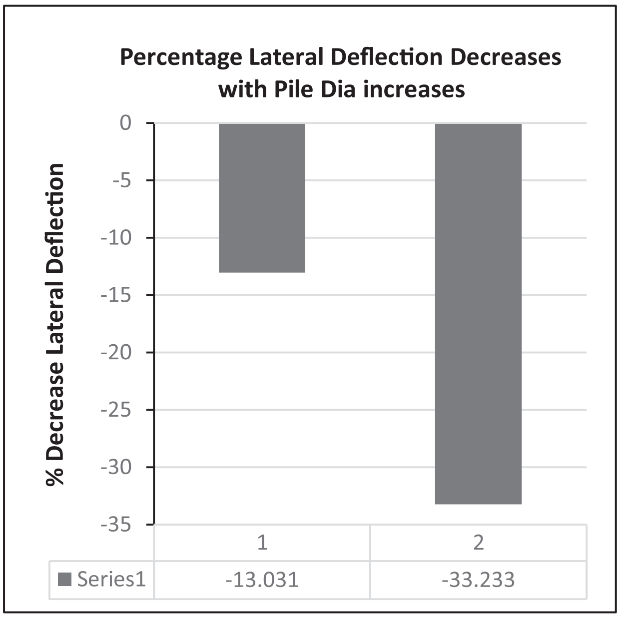


Figure 9b - Percentage reduction in pile lateral deflection as the diameter of pile increases (z = -20m)

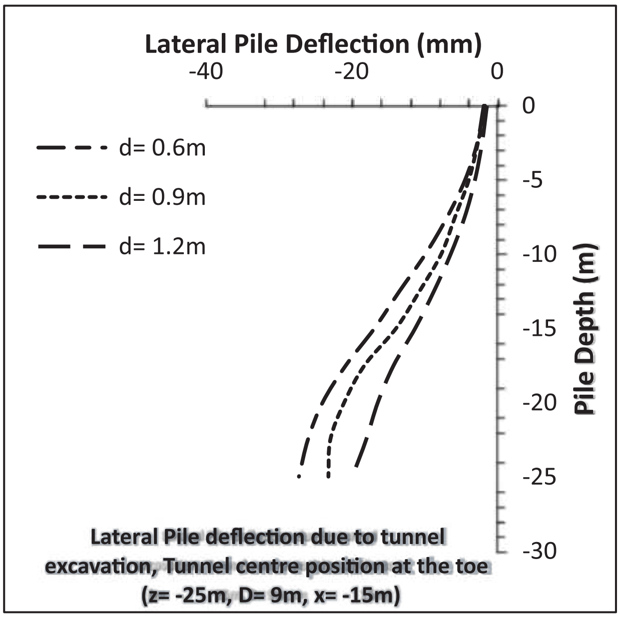


Figure 10a - Pile lateral deflection with varying pile diameter (z= -25m)

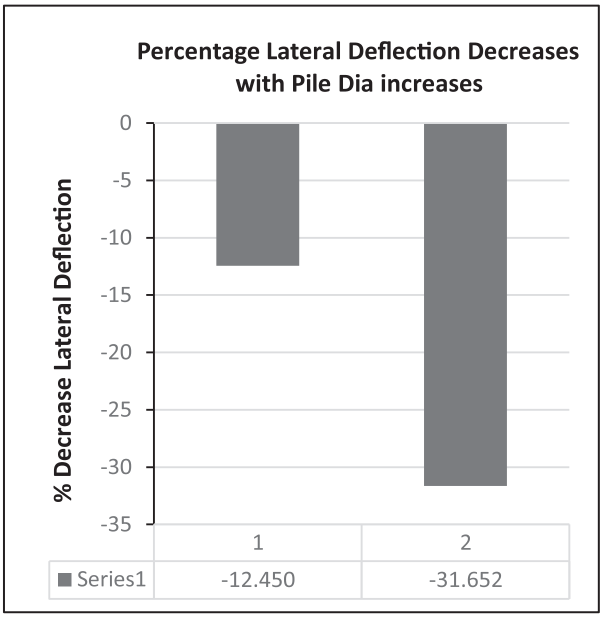


Figure 10b - Percentage reduction in pile lateral deflection as the diameter of pile increases (z = -25m)

4.2 Pile Bending Moment

Figures 11 and 12 provide a visual representation of how bending moments change in response to variations in tunnel and pile diameters, respectively. This comprehensive analysis was conducted to understand how different tunnel and pile dimensions affect bending moments. In the case of Fig. 11a, the analysis involved placing the tunnel at, z= -20m & x= -15m, with a pile diameter of 0.9 m. Tunnelling was carried out with diameters of 6.75m, 9m, and 13.5m, which correspond to 7.5 times, 10 times, and 15 times the pile diameter (D= 7.5d, 10d, and 15d, respectively). The study specifically focused on investigating lateral displacements of the pile at depths of -20m for tunnel diameters of (D= 7.5d, 10d, and 15d), while maintaining a constant vertical tunnel position at -20m and -25m. In Fig. 12a, the analysis examined variations in bending moment concerning changes in pile diameter. The tunnel was located at (z= -20m, x= -15m) with a tunnel diameter of 9m, and pile diameters of 0.6m, 0.9m, and 1.2m (d= 0.6d, 0.9d, and 1.2d) are considered. The research specifically aimed to analyze lateral displacements of the pile at depths of -20m for pile diameters of (d = 0.6d, 0.9d, and 1.2d), while maintaining a constant vertical tunnel position at -20m.

In the context of pile bending moment at a depth of -20m with varying tunnel diameters, Fig. 11b shows notable fluctuations. Particularly, when the tunnel diameter reached 9m (equivalent to 10 times the pile diameter, D = 9m or 10d), the bending moment exhibited a 66% increase compared to the situation when the tunnel diameter was 6.75m (equivalent to 7.5 times the pile diameter, D = 6.75m or 7.5d). Furthermore, under the conditions of D = 9m or 10d, the bending moment experienced a substantial 142% increase in comparison to the scenario with D = 6.75m or 7.5d. Regarding the bending moment of the pile at a depth of -20m with varying pile diameters, Fig. 12b displays significant variations. Specifically, when the pile diameter was 0.9m, the bending moment increased by 6% in contrast to the scenario with a 0.6m pile diameter. Moreover, when the pile diameter was 1.2m the bending moment experienced a substantial increment 12% compared to the situation with a 0.6m pile diameter.

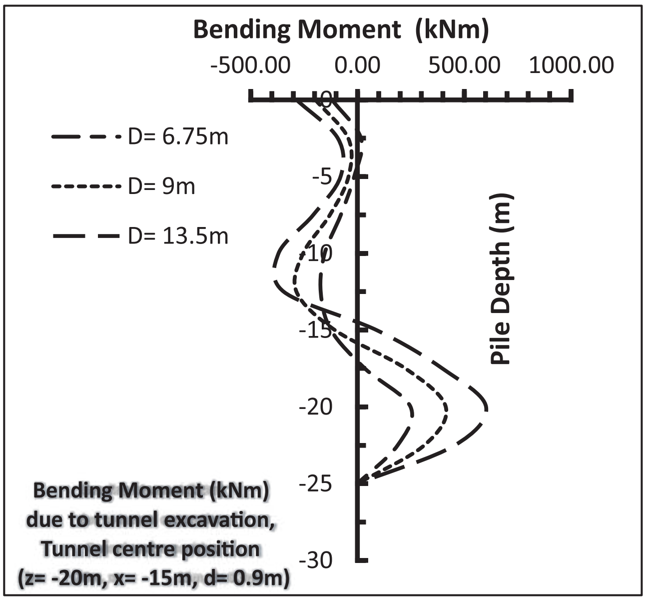


Figure 11a - Pile bending moment with varying diameter of tunnel (z= -20m)

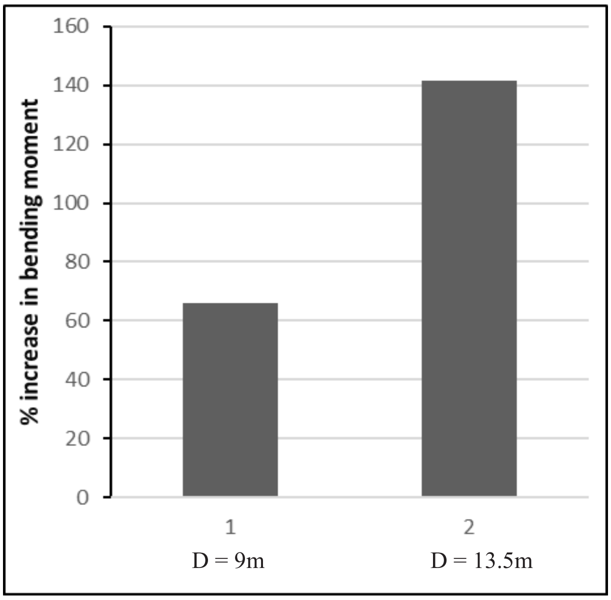


Figure 11b - Percentage increase in pile bending moment with the increase in tunnel diameter (z = -20m)

5. MATHEMATICAL MODELLING

It is evident from the above-mentioned graphs and can be contradictory that the lateral deflection and bending moment of piles around the vicinity of tunnelling cannot be attributed to just single parameter or single boundary condition, i.e., geometrical dimensions of pile or tunnel, from the many as discussed in detail in the above sections. When a tunnel excavation takes place, the piles deflect as evident from the graphical patterns shown above by a combined actions of every independent parameter taking part such as pile diameter, pile length, tunnel diameter, tunnel depth, horizontal distance of tunnelling from nearest pile, elastic modulus of soil and elastic modulus of pile. In tunnel-pile-soil interaction, these parameters create a network that results in the shown graphical patterns. These justify the findings from literature that to predict the deflection and bending moment of pile during tunnelling in a better way, it should be observed and studied under multiple variables at the same time.

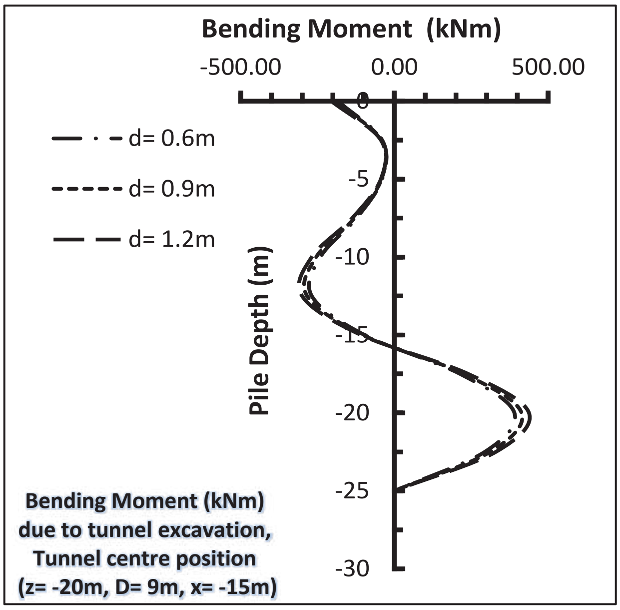


Figure 12a - Pile bending moment with varying pile diameter (z= -20m)

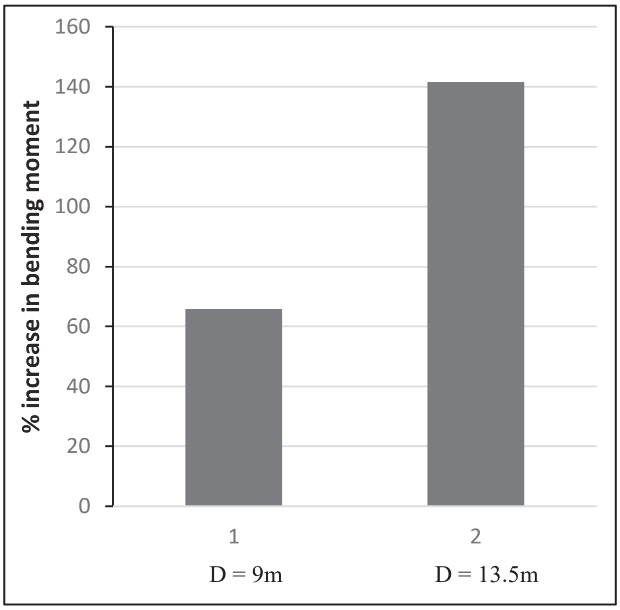


Figure 12b - Percentage increase in pile bending moment as the diameter of pile increases (z=20m)

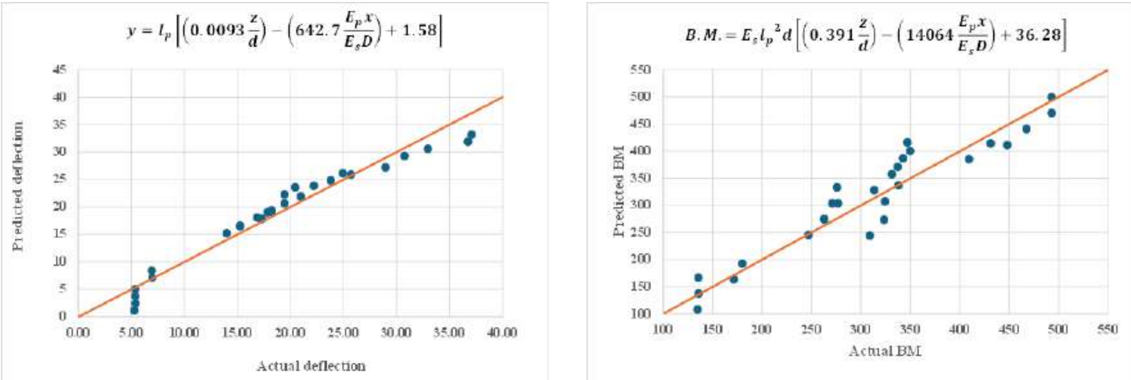
Keeping this in view, a prediction model is proposed for both, i.e., deflection and bending moment in static condition involved in this study which is presented in Eqn. 1-2. The equations are empirically adjusted and dimensionally stabilized using numerous trial and errors along with multiple regression analysis.

For deriving the equation, seven independent variable parameters are used, i.e., pile diameter (d), pile length (lp), tunnel diameter (D), tunnel depth (z), horizontal distance of tunnelling from nearest pile (x), elastic modulus of soil (Es) and elastic modulus of pile (Ep) which decides the pile deflection (y) and pile bending moment (BM). All these parameters are related to deflection and bending moment of pile using linear fit concept by regression analysis. The reason behind choosing these variables is the crystal-clear following of trend as predicted from literature and current study. The relation between calculated and predicted pile deflection and bending moment are also shown in Fig. 13. All the formed equations give prediction under 95% confidence band. The performance factors such as standard error, root mean square error (RMSE), Pearson's correlation coefficient (R^2) and significance factor (F) are shown in Table 3. The overall significance factor (F) for all the equations came out be less than 0.05 as shown in table. This concludes that one can reject the null hypothesis and accept the alternative hypothesis which proves that variables are dependent on each other. The equation is significant for 95% confidence band. If R^2 is 1 (which ideally should be in between 0.8 and 1) and RMSE is 0, the model is treated as excellent. For the relationship presented in Eq.1 for pile deflection, the values of R2 and

RMSE were found as 0.94 and 2.05mm, respectively and hence it can be concluded that the pile deflection can be very well predicted using this model. Same conclusions can be made using the performance factors of other equations as shown. From the graphs drawn about calculated and predicted breakage along the perfection axis, it can be said that the deflection and bending moment can be very well predicted using each mathematical model for respective cases.

Table 3 - Equations and their performance factors

Equation No.	R^2	RMSE	F	Standard Error
1	0.94	2.05 mm	7.8×10^{-17}	0.09 mm
	$y_{st} = l_p\left[\left(0.0093\frac{z}{d}\right) - \left(642.7\frac{E_p x}{E_s D}\right) + 1.58\right]$			
2	0.88	34.29 kNm	8.2×10^{-13}	2.95 kNm
	$BM_{st} = E_s l_p{}^2 d\left[\left(0.391\frac{z}{d}\right) - \left(14064\frac{E_p x}{E_s D}\right) + 36.28\right]$			



(a) Static pile deflection (b) Static pile bending moment

Figure 13 - Calculated vs predicted values of pile deflection and bending moment

6. CONCLUSIONS

This comprehensive 3D finite element analysis has delved deeper into the repercussions of horizontal tunnelling on a 2×2 pile group within a saturated medium-stiff silty clay soil. The outcomes of this study underscore the substantial impact of tunnelling activities on adjacent piles, leading to significant bending moments and lateral deflections. Several key conclusions emerge from current findings.

1. Variation in Tunnel Diameter:
   i. Lateral deflection consistently increases with tunnel diameter across all scenarios. Notably, at depths of 20m and 25m, the lateral deflection displayed significant fluctuations as tunnel diameter varies. Specifically, when the tunnel diameter reaches 9m (equivalent to 10 times the pile diameter, D=9m or 10d), lateral deflection increased by approximately 60%, compared to a 6.75m tunnel diameter (equivalent to 7.5 times the pile diameter, D = 6.75m or 7.5d). Furthermore, under conditions of D = 9m or 10d, the lateral deflection experienced a substantial average increase of around 145%, compared to the scenario with D = 6.75m or 7.5d.

ii. Noticeable fluctuations are observed in case of pile bending moment at a depth of -20m with varying tunnel diameters as shown in Fig. 11b. Specifically, when the tunnel diameter reached 9m (equivalent to 10 times the pile diameter, D = 9m or 10d), the bending moment exhibited a 66% increase compared to a 6.75m tunnel diameter (equivalent to 7.5 times the pile diameter, D = 6.75m or 7.5d). Furthermore, under the conditions of D = 9m or 10d, the bending moment experienced a substantial average increase of around 142%, compared to the scenario with D = 6.75m or 7.5d.

2. Variation in Pile Diameter:
   i. Regarding lateral deflection of the pile at depths of -20m and -25m with varying tunnel diameters (Fig. 9 & Fig. 10), significant variations were evident. Specifically, when the pile diameter was 0.9m, the lateral deflection decreased by approximately 13%, compared to a 0.6m pile diameter. Moreover, the lateral deflection exhibited a substantial average reduction of around 33%, compared to the scenario with a 0.6m pile diameter.
   ii. Concerning the bending moment of the pile at a depth of -20m with varying pile diameters (Fig. 12), significant variations were also observed. Specifically, when the pile diameter was 0.9m, the bending moment increased by approximately 6%, compared to a 0.6m pile diameter. Furthermore, with a 1.2m pile diameter, the bending moment experienced a substantial average increment of around 12%, compared to the scenario with a 0.6m pile diameter.
3. In case of urban areas, where the lack of space for farther placement of tunnel from pile raft can cause difficulties in development requirements, an optimum approach with minimal consequences can be chosen by taking this study into consideration.
4. The equation proposed for each case from multiple regression analysis holds a good relation between the measured and predicted values.
5. All the equations have overall significance factor less than 0.05. This concludes that one can accept the alternate hypothesis and accept that the proposed equations are significant for 95% confidence level. Also, the corelation coefficient of each equation lies between 0.8 and 1 which means the equation holds very strong relationship.
6. These findings underscore the complex relationships between tunnel diameter, pile diameter, lateral deflection, and bending moment, providing valuable insights for the design and evaluation of structures in tunnelling proximity within saturated clay soils. Further research and analysis are recommended to explore additional factors and scenarios for a more comprehensive understanding of this complex interaction.

7. FUTURE RECOMMENDATIONS

- Though, it is evident from the graphs that the pile deflection and bending moment are not dependent of few parameters, not all the parameters involved in mathematical model have been analyzed. A further study may include further inclusion of other parameters as well so as to understand and predict the pile behaviour appropriately.
- A large-scale model test may be conducted to verify and validate the software outcomes with experimental results to increase the weight of trust in final conclusions.

- The current study does not include the dynamic effect of/during tunnelling on nearby pile. Hence, further study may include some dynamic effects also to increase the effectiveness of pile behaviour prediction.

List of Abbreviations

TPS	Tunnel-Pile-Soil
TPSI	Tunnel-Pile-Soil Interaction
m	Meter
dia	Diameter
NGL	Natural Ground Level
FEM	Finite Element Method
BEM	Boundary Element Method
FDM	Finite Difference Method

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