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Numerical analysis of displacements in concrete pile foundations induced by adjacent tunnel excavation in sandy soils

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ABSTRACT

Tunneling over a field leads to surface, subsurface settlement, and lateral deformation. Tunnels built to nearby foundations of building, produces a ground loss, which affects the foundation behavior. This paper aimed to study the displacement behavior of existing pile foundations in the sandy ground during tunnel excavation using the numerical software PLAXIS 3D. The comparison of published results from various numerical analysis software was used to verify the validity of the PLAXIS 3D approach. However, the uncertainties of material properties of soil in satisfying the parameters of the Mohr-Coulomb model were assumed in the analyses. Both single pile and pile group effects due to tunneling are analyzed. A total of 21 FE analyses were involved in predicting the regular plane strain responses of piles such as lateral displacement and vertical displacement identified during the excavation process of tunneling. The parametric research on pile and pile group responses involved the study of the effect of relative density, pile location from tunnel centerline, pile diameter, pile length, and volume loss. Based on the safe limiting value of lateral and vertical displacement as 5 mm and 10 mm respectively, recommendations for the tunnel's location concerning the adjacent existing piles were provided.

Keywords: Tunnel excavation; Volume loss; Numerical analysis; Pile displacement; Sandy ground.

1. INTRODUCTION

Tunneling has an impact on structural foundations which is certainly relevant for piled foundations. In underground construction, it is imperative to account for the physical and chemical characteristics of the strata. Shield machines are extensively employed in projects like subways and tunnels due to their high level of mechanization, resilience to environmental variations, and versatility in adapting to diverse geological conditions [1]. Since tunnels are typically found at deep levels, they will be adjacent to these pile foundations. To control the risky settlements of these piles, it is also necessary to investigate the impact of tunneling activities on the adjacent piles in terms of extra stresses and displacements. Many researchers have used experimental methods to examine the factors that might reduce the impact of tunnel excavation on adjacent piles [2] and to deliver realistic results for verification against the result of numerical methods. Most of these investigations were carried out in a laboratory environment using photogrammetry, photoelasticity, small-scale testing models, and centrifuge tests. Case studies were used to validate the result of numerical methods by various researchers [3, 4].

The most essential element in designing tunnels is to use various modelling approaches of tunnel-soil-pile interaction. These various methodologies, which are based on various approaches such as analytical, numerical, and experimental, produce varying findings in terms of pile behaviour due to tunneling. Especially the closed-form solutions of analytical method, involve simple computation procedures when employing boundary element techniques [5]. However, for complex issues and circumstances, the specified techniques do not provide adequate estimates for the issues of complexity and circumstances. Some of them focused chiefly on numerical simulations [6, 7], where their analyses were based on the interaction of tunnels- pile and in some cases, they used various constitutive models such as Mohr-Coulomb, elastoplastic, elastic, displacement control model,

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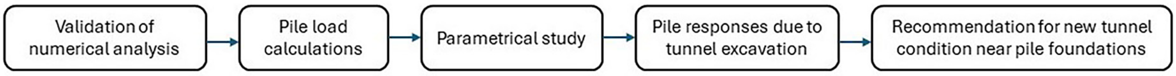

Figure 1: Methodology.

hardening soil model, and soft-soil model. On the other hand, the numerical methods based on the finite element technique are vital in tunneling analysis, especially the impacts of tunneling on the neighbouring piles [8].

From an engineering perspective, the interaction dynamics between the surrounding subsoil and twin tunnels are inherently more complex and risky than those associated with a single tunnel. This heightened complexity can significantly compromise the serviceability of nearby existing structures. Therefore, it is crucial to closely monitor and understand the critical interaction behavior between the tunnels and adjacent pile-supported structures [9]. The discrete element approach has shown to be promising for difficult soil–structure interaction problems involving soil movement and particle loss near an existing underground structure, which accounted for the interaction and relative movement of soil particles at the microscale level. However, most of the available theoretical and physical models are mainly based on macroscale evaluations the major limitations of the DEM [10].

The tunnel excavations, which are extremely near to the adjacent buildings cause vertical and lateral soil movement on piles. As a result, the axial responses including axial force and settlement are induced. Moreover, it leads to lateral responses such as pile deflection and bending moment. The objective of the work includes studying the displacement behavior of existing pile foundations inside the influencing zones during tunnel excavation and providing suggestions for the location of new tunnels, and nearby pile foundations based on extensive parametric studies. The paper presents the computation of pile responses due to tunnel excavation in the sand using finite element software PLAXIS 3D. In addition, it has explained the tunnel-soil-pile interaction characteristics through the influence zones and significant recommendations are provided for the design of tunnel consequences. The methodology of displacement behaviour of existing pile foundations in the cohesionless ground during tunnel excavation is shown in Figure 1.

2. NUMERICAL MODELLING OF TUNNEL EXCAVATION NEAR PILE FOUNDATION

Numerical analysis by PLAXIS 3D was considered in terms of ground heterogeneity, soil nonlinear effects, different soil models, 3D effects, diverse tunnel configurations, interaction with adjacent buildings, and tunnel method of construction and sequence. The assumption that soil fill is isotropic and homogeneous and supposed to follow the elastic-plastic stress-strain relationship and obey the Mohr-Coulomb failure criterion was followed. This non-linear model is based on the soil characteristics that are commonly recognized in real-world settings. However, this model does not capture all the non-linear aspects of soil behaviour. As per [11], the parameters of the Mohr-Coulomb model were used for pile-tunnel interaction in the sand, all the analyses were conducted in the sands of homogeneous condition, and a single borehole was created and defined with the material properties of soil as per Mohr-Coulomb model parameters.

For modelling, the tunnel lining and its interaction with the surrounding soil were done using plates and interfaces. The curved borders inside the mesh were modelled using fully iso-parametric elements. Mesh convergence studies were performed before parametric analysis during validation, to study the effect of element size by changing the coarseness in PLAXIS 3D from very coarse to very fine. From mesh convergence studies, it was found that medium-mesh size with a soil coarseness factor of 0.75 was giving better results for all the cases. Additionally, the plates were used to depict a thin layer of two-dimensional TBM with significant flexural rigidity. The volume elements were used in modelling the uniform piles and the material properties of concrete Young's Modulus, 'E' and Poisson's ratio, 'ν' are assigned to it. The interface between the pile and surrounding soil is represented using 12 noded interface elements, while the pile and surrounding soil were both modelled as volume elements using ten noded tetrahedral elements. The material properties of interface elements were the same as the surrounding soil, but with a strength reduction factor (R_{inter}) of 0.67 to account for the reduction in interface strength [12]. The pile group analysis consists of 4 numbers of 2 × 2 piles with pile caps of the same concrete material properties resting on the ground surface. PLAXIS 3D allows for automatic mesh generation of quadratic tetrahedral 10-node elements to model the deformations and stresses in the soil. The 3D finite element analysis provides plane strain results, which are essential for accurately capturing the complex interactions between the tunnel, pile, and surrounding soil. This approach is necessary because it allows for a more realistic representation of the stress and deformation patterns in the soil, which are critical in understanding the impact of tunnel construction on adjacent pile-supported structures. By considering the plane strain conditions, the analysis can effectively model the behavior of the soil and its influence on both the tunnel and the piles, ensuring a comprehensive assessment of potential risks and ensuring the stability of nearby structures.

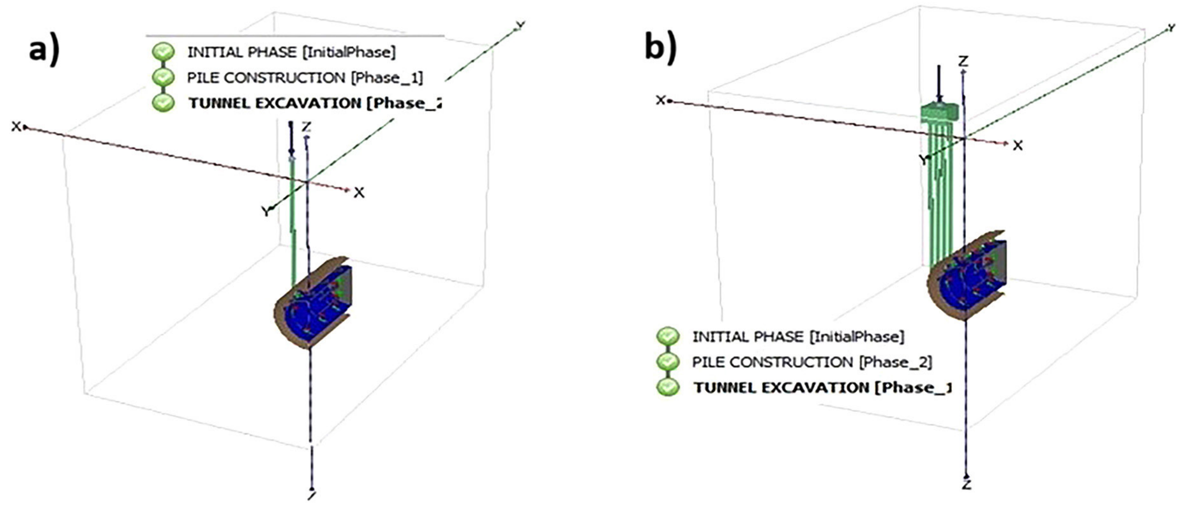

Figure 2: Phased calculations. (a) single pile; (b) pile group.

The modelled existing single pile or pile group in sands was activated and assigned an axial load. Realistic modelling of excavation and construction activities was carried out by activating and deactivating clusters of components, adding loads, and so on for the simulations of calculations. All the observations that are mentioned are performed in stages as shown in Figure 2a and 2b. The output which consists of a deformed mesh was analyzed to determine the characteristics of ground and pile displacement. It was observed that the different forms of pile displacements such as lateral displacement (Ux) along the X axis, longitudinal displacement (Uy) along the Y axis, and vertical displacement (Uz) along the Z axis were noticed.

3. VALIDATION OF PLAXIS 3D RESULTS FOR PILE RESPONSES

The results of the centrifuge test and FE models using other numerical software reported in the literature were used to verify the pile response results obtained by PLAXIS 3D. The obtained single pile settlement responses using PLAXIS 3D, simulating tunnel excavation in the sand for various volume losses from 1% to 5% were compared with the results of the Centrifuge test conducted by [13]. During the process of analysis, the settlement of the pile was determined at different pile locations concerning the tunnel centerline (3.75 m and 7.5 m). The soil and the material properties of the pile model which are provided in Table 1 were utilized for the finite element analysis. Therefore, the comparison of the results shows agreement as shown in Figure 3.

The comparison of published results from various numerical analyses such as GEPAN [15], PRAB [5], and PGROUPN [14], was used to verify the validity of the PLAXIS 3D approach. The material properties of soil and pile that are used in the analysis are given in Table 2. However, the uncertainties of soil properties in satisfying the parameters of the Mohr-Coulomb model were assumed in the analyses. Both single pile and pile group effects due to tunneling are analyzed as shown in Figure 4a and 4b. Thus, it was assumed that no loading was acted upon the pile head.

Both lateral and vertical displacements of the pile were analyzed in terms of volume losses with a common design value of 1% and an extreme value of 5% accordingly. The corresponding simulation of volume loss is achieved by varying percentages of contraction. The lateral deflections of PLAXIS 3D were compared with the other results of numerical analyses that were reported in the literature. An excellent agreement is found and the maximum lateral deflection is occurred above the tunnel axis as shown in Figures 5 and 6. Similarly, in Figures 7 and 8, the results of vertical displacement of PLAXIS 3D are found to agree with the other results of numerical analyses. Since the current research had involved the examination of pile group responses to tunneling, the validity of PLAXIS 3D was also examined for the pile group effect among the other numerical analysis software. A four-number of 2 × 2 pile group is shown in Figure 3b was positioned near the tunnel at a distance of 4.5 m.

Therefore, it was assumed that no loading was acted upon the pile cap. In addition to that, the piles were spaced at a distance of 2.4 m. A favorable agreement is observed from the Figure 9 to 12 for both front and back pile responses in comparison with the results of other numerical analysis software for a volume loss of 1%. Thus, it was observed that the results were over-predicted with marginal variation. The results of the numerical analyses were compared with the results that were reported in the literature. Since the comparison provided

Table 1: Material Properties [13].

DESCRIPTION	SOIL	PILE	UNIT
Unsaturated unit weight, (γ_{unsat})	15.6	24	kN/m^3
Young's Modulus, E	6.0E + 04	3.1E + 07	kN/m^2
Poisson's ratio, ν	0.35	0.15	–
Friction angle, φ	32	–	0

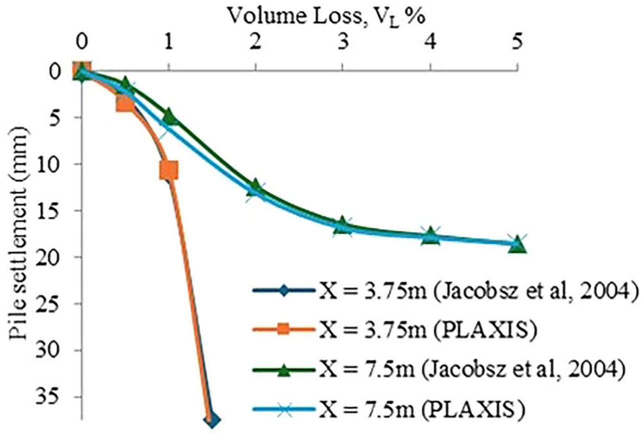

Figure 3: Comparison of pile settlement.

Table 2: Material properties of soil and pile [14].

DESCRIPTION	SOIL	PILE (SINGLE AND GROUP PILE)	UNIT
Young's Modulus, E	2.4×10^4	3.0×10^7	kN/m^2
Poisson's ratio, ν	0.5	0.15	–

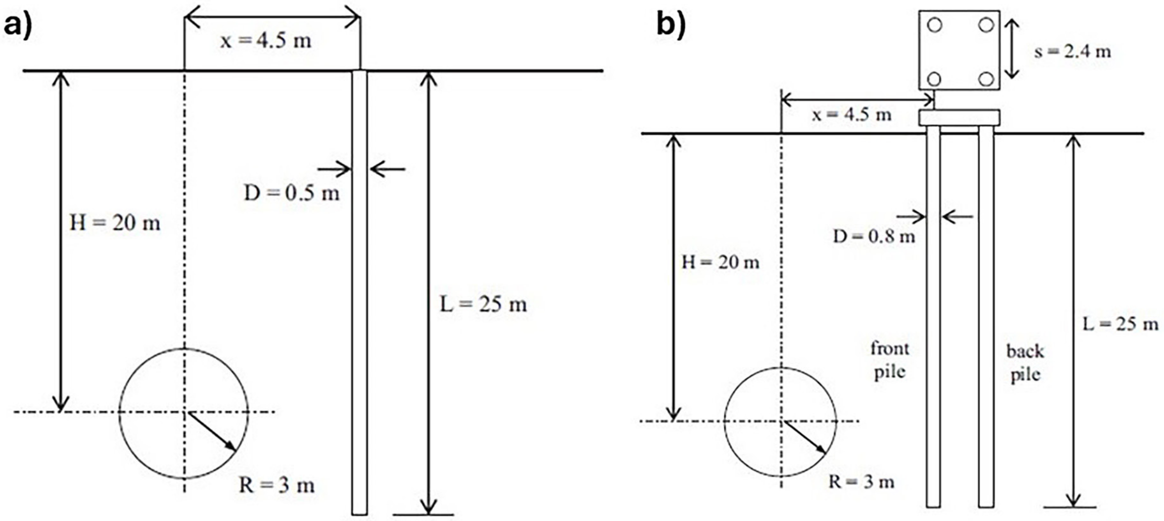

Figure 4: Pile and tunnel geometry [10]. (a) single pile; (b) pile group.

a good agreement between the results of the literature and the proposed numerical analysis, the FE models confirmed the capacity to replicate the geotechnical behaviour of tunnel-soil-pile interactions. The assumptions made in the Mohr-Coulomb (MC) model that the sand layers would behave as elastic-perfectly plastic materials were found to be valid throughout the parametrical study.

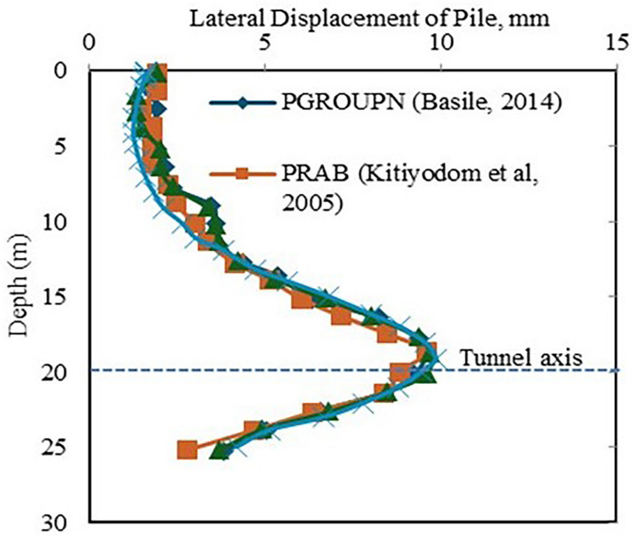

Figure 5: Comparison of lateral displacement ($V_L = 1\%$).

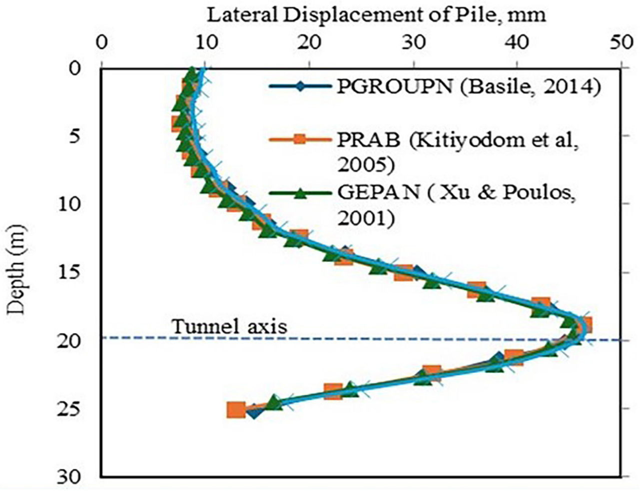

Figure 6: Comparison of lateral displacement ($V_L = 5\%$).

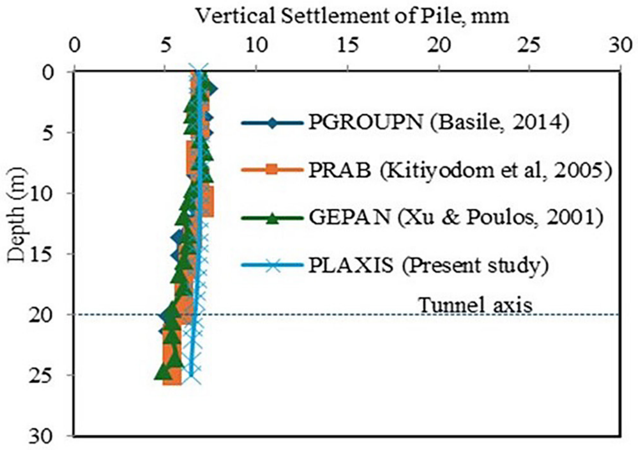

Figure 7: Comparison of vertical displacement ($V_L = 1\%$).

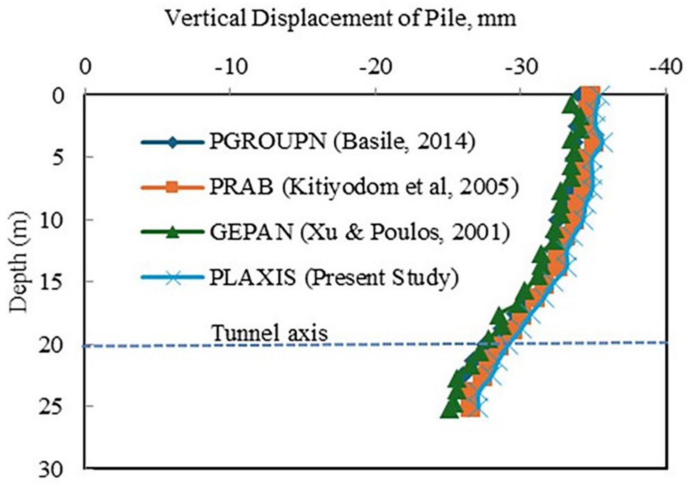

Figure 8: Comparison of vertical displacement (V_L = 5%).

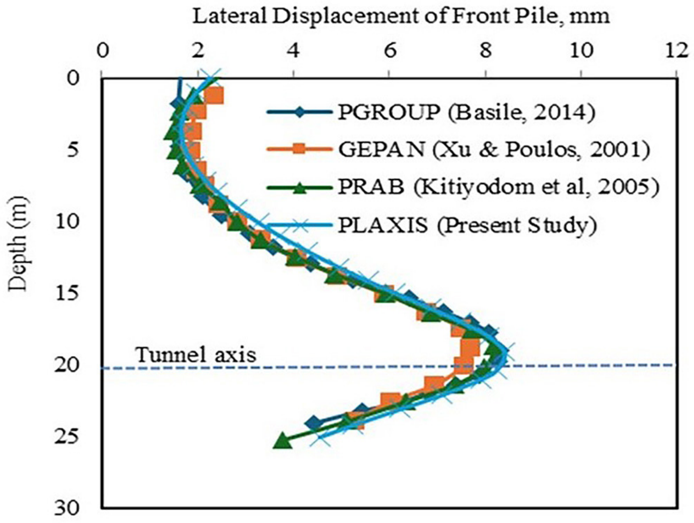

Figure 9: Comparison of lateral displacement for V_L = 1% (front pile).

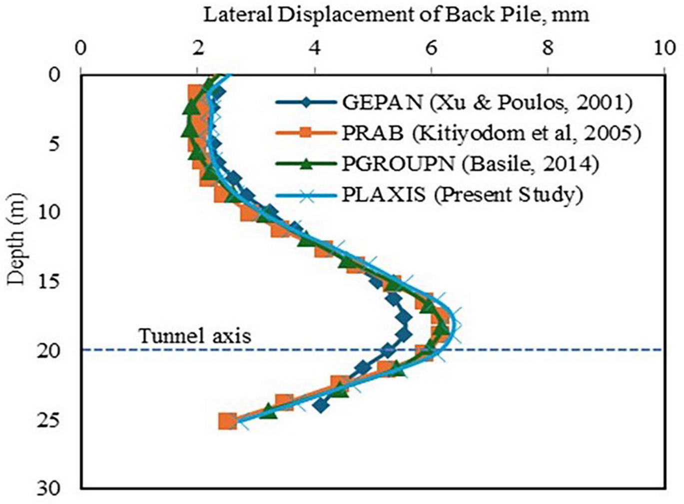

Figure 10: Comparison of lateral displacement for V_L = 1% (back pile).

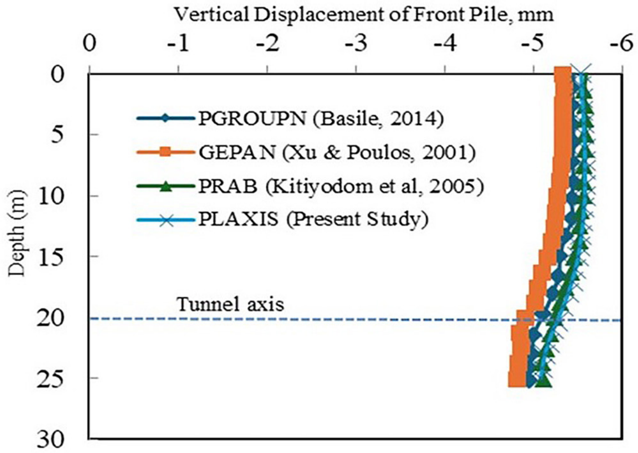

Figure 11: Comparison of vertical displacement for V_L = 1% (front pile).

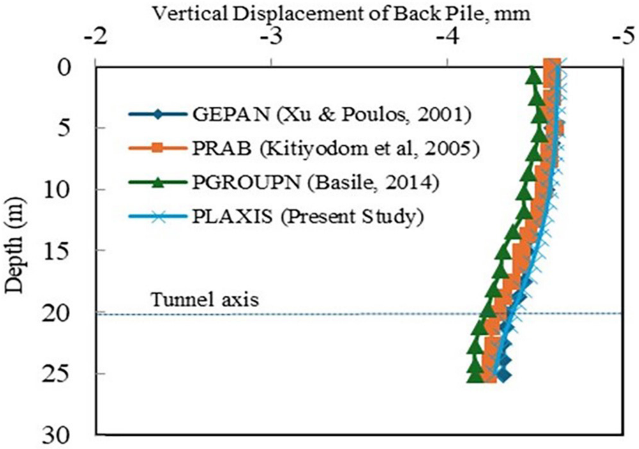

Figure 12: Comparison of vertical displacement for V_L = 1% (back pile).

4. TUNNEL EXCAVATION INDUCED PILE DISPLACEMENTS

The study is mainly focused on the settlement and the lateral displacement along the pile length. The bending of piles was not investigated in this study because the limiting value of lateral displacement was considered as 5mm, which directly indicates the restriction of bending of piles. The responses of both isolated single piles and piles in the group are determined. The pile and pile group characteristics were observed for different volume losses. The regular plane strain responses of piles such as lateral displacement and vertical displacement were identified during the excavation process of tunneling. The effect of the significant pile parameters such as pile length, pile diameter, and location of pile concerning tunnel axis was examined at various phases during tunneling with different densities of sand.

4.1. Pile load calculation for parametric analysis

The pile responses of both single and group piles due to the tunneling activities were studied in loaded conditions. The ultimate vertical load capacity was calculated by a separate numerical analysis for a single pile and pile group. The safe load on single and group piles was estimated as per [16, 17]. The corresponding load settlement curve is shown in Figure 13a and 13b respectively.

Since the average tunnel size of the metro railway system in most of the Indian cities and other countries has 6 meters as external diameter, the tunnel diameter, D = 6 m was used for further parametrical research on pile responses towards tunneling. A constant tunnel axis depth, H = 20 m, was adopted throughout the study to understand pile foundations' responses near deeper tunnels. Especially, the responses of the pile have been studied at three different tunnel levels namely, tunnel crown, tunnel spring line, and tunnel invert. In this research, the safe limiting value of vertical and sideways displacement of pile foundations due to tunneling was considered at a conservative value of 10 mm [18, 19] and 5 mm [16] respectively.

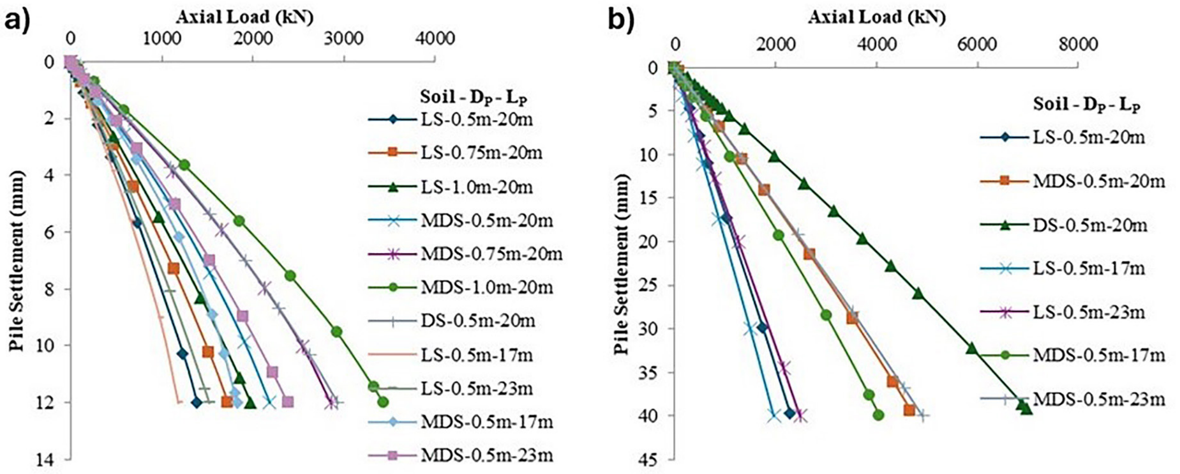

Figure 13: Load settlement curve. (a) single pile; (b) pile group.

The tunnel excavation had caused displacement around it especially, above the tunnel axis in the sand. Moreover, the tunnel excavation had produced significant displacement primarily in the plane strain condition i.e., along lateral and vertical directions. Hence, apart from the settlement induced by axial loading, lateral and vertical pile or pile group displacements, particularly due to tunnel excavation, were studied for various influencing factors.

The material properties of the pile given in Table 2 were used for the parametric research. The material properties of different relative densities of sand and TBM are given in Tables 3 and 4. The modelling sequences and output analyses of single pile and pile groups due to tunneling are shown in Figures 14 and 15. In the parametric research, the obtained results of pile or pile group displacements from FE analysis are represented in graphs with normalized depth 'Zp/H', where Zp is the depth of the pile. Therefore, the value of Zp/H is zero at the ground surface level and unity at the tunnel axis level. Except in the study of the influence of volume losses on pile responses, Ground volume loss due to tunneling was adopted as 0.5% for all the other parametrical studies.

4.2. Effects of relative density

The effects of the relative density of sand were studied from the displacement responses of a single pile and pile group placed at the horizontal distance, x = 4.5 m from the tunnel centerline in three different densities of sand and their material properties are given in Table 3. Figure 16a shows the lateral displacement of a single pile located at 4.5 m from the tunnel centerline in loose sand (LS), medium-dense sand (MDS), and dense sand (DS).

The pile displacement towards the tunnel increased gradually beyond the pile depth of 0.3H and was found maximum at depth 0.75H in loose, medium dense, and dense sand respectively. However, beyond the depth of 0.75H, the pile lateral displacement was decreased. It was observed that the increased soil parameters in medium dense and dense sand had decreased lateral displacement of the pile than in loose sand. Similarly, Figure 16b represents the lateral displacement of the front and back pile in a pile group located at 4.5 m from the tunnel centerline to the front pile in loose, medium-dense, and dense sand. It is to be noted that the lateral displacement of the back pile was more than the front pile up to the pile depth of 0.5H in all three different relative densities of sand. However, beyond 0.5H and up to the tunnel axis, the lateral displacement of the front pile was more than the back pile. In particular, at pile depth 0.75H the lateral displacement of the front pile was observed to be maximum. However, beyond the depth of 0.75H, the lateral displacement was decreased in both the front and back pile. Similar to the lateral displacement of a single pile, the increased soil parameters in medium dense and dense sand had decreased lateral displacement of both front and back piles than in loose sand.

The vertical displacement of single pile located at a distance of 4.5 m from the tunnel centerline in loose, medium dense, and dense sand was observed as shown in Figure 17a. The vertical displacement of the pile in loose, medium dense and dense sand due to tunnelling was observed to be 10.1 mm, 5.6 mm, and 4.8 mm respectively. However, in medium dense and dense sand, the vertical displacement had decreased gradually to 5.5 mm and 4.6 mm respectively at the tunnel axis. The reason might be due to the resistance offered by the increased soil parameters in medium-dense and dense sand at a deeper depth than in loose sand. The vertical displacement of the pile group with front pile located at 4.5 m from the tunnel centerline in loose, medium dense, and dense

Table 3: Material properties of sand of various relative densities [20–22].

PARAMETER	LOOSE SAND (LS)	MEDIUM DENSE SAND (MDS)	DENSE SAND (DS)	UNIT
Material model	MC	MC	MC	–
Material behaviour	Drained	Drained	Drained	–
Unsaturated unit weight, (γ_{unsat})	16	17	18	kN/m^3
Saturated unit weight, (γ_{sat})	19	20	21	kN/m^3
Young's Modulus, E	1.5E + 04	3.0E + 04	4.5E + 04	kN/m^2
Poisson's ratio, ν	0.3	0.35	0.4	–
Cohesion*	0.1	0.1	0.1	kN/m^2
Friction angle, φ	30	35	40	0
Dilatancy angle, ψ	0	5	10	0

Table 4: Material properties of TBM.

PARAMETER	VALUE	UNIT
Material behaviour	Elastic	–
Nominal Stiffness, EA	8.2E + 06	kN/m
Flexural Rigidity, EI	8.38E + 04	kNm^2/m
Equivalent thickness, d	0.35	m
Weight	38.5	kN/m/m

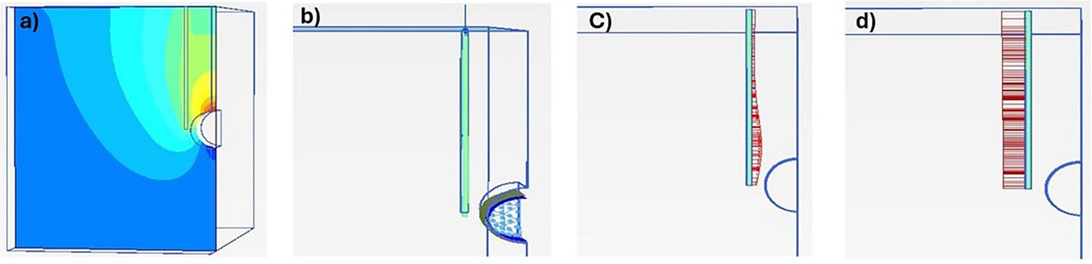

Figure 14: FE modelling and analysis of single pile due to tunneling. (a) displacement shading; (b) pile displacement; (c) lateral displacement; (d) vertical displacement.

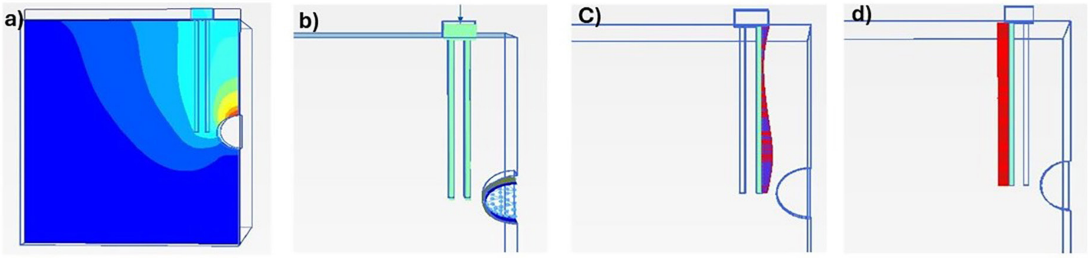

Figure 15: FE modelling and analysis of pile group due to tunneling. (a) displacement shading; (b) pile group displacement; (c) front pile lateral displacement; (d) back pile vertical displacement.

sand was observed as shown in Figure 17b. The vertical displacement of the front pile in the pile group was observed to be 7.8 mm, 5.3 mm, and 4.6 mm in loose, medium dense and dense sand respectively. The vertical displacement of the back pile which was behind the front pile at 2 m spacing between centre to centre was observed to be 7.1 mm, 4.8 mm, and 4 mm in loose, medium dense, and dense sand respectively.

The increased horizontal distance of the back pile from the tunnel centreline in comparison to the front pile might be the reason for decreased vertical displacement than the front pile. From Figure 16 and 17

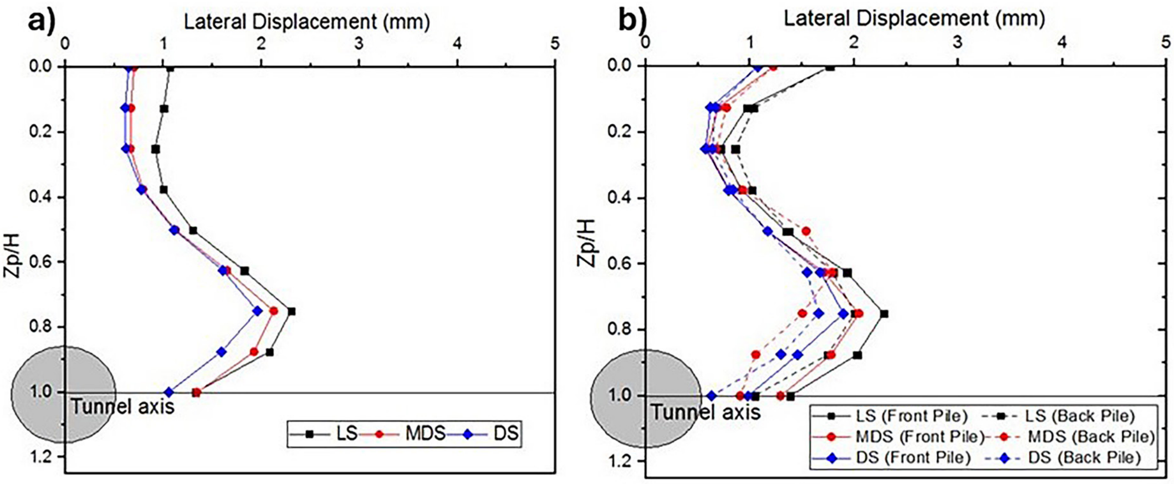

Figure 16: Lateral displacement in different relative density of sand. (a) single pile; (b) pile group.

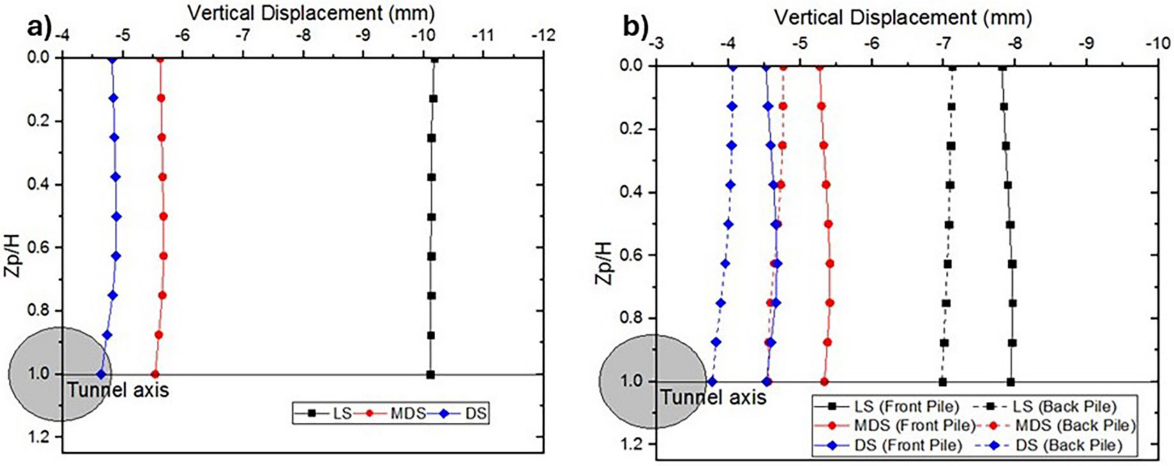

Figure 17: Vertical displacement in different relative density of sand. (a) single pile; (b) pile group.

it was observed that for tunnel size 6 m and volume loss 0.5% the pile foundation responses in medium dense and dense sand were almost similar. The pile responses of dense sand were less than the medium-dense sand and henceforth for further parametric studies, the pile responses were examined for loose and medium-dense sand alone.

4.3. Effects of horizontal distance of pile ‘x’ from tunnel centreline

The effect of the location of the pile from the tunnel centerline was studied by analyzing the pile placed at different horizontal distances ‘x’ from the tunnel centerline as shown in Figure 18a and 18b. From Figure 18a it was observed that the lateral displacement obtained after the analysis of piles placed at different horizontal distances x = 4.5 m, 6.0 m, and 7.5 m in loose sand were 1.06 mm, 1.15 mm, and 1.51 mm at ground surface. To find the distance of insignificant responses, the horizontal distance between the pile and tunnel centreline, x = 15 m was chosen for the analysis. Except for the pile located at 15 m, the lateral displacements of the pile at the other three locations x = 4.5 m, 6.0 m, and 7.5 m decreased gradually up to depth 0.4H and increased up to 0.75H as 2.3 mm, 2.02 mm, and 1.63 mm respectively. The lateral displacement of the pile at x = 15 m decreased gradually from 0.4 mm to 0.07 mm, from the pile head at surface level to the pile tip at tunnel axis respectively. It was observed that the increased distance of the pile from the tunnel centreline had decreased lateral displacement below the pile depth of 0.4H.

From Figure 18b it was observed that the vertical displacement obtained after the analysis of piles placed at different horizontal distances x = 4.5 m, 6.0 m, 7.5 m, and 15 m in loose sand were 10.1 mm, 7.9 mm, 6.0 mm,

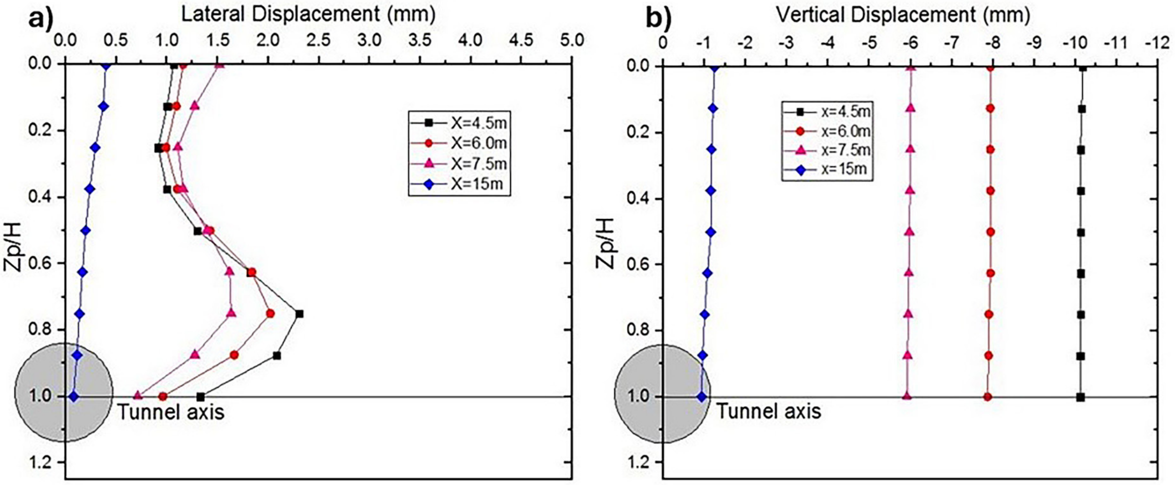

Figure 18: Pile at different horizontal distance 'x' from tunnel centreline in loose sand. (a) lateral displacement; (b) vertical displacement.

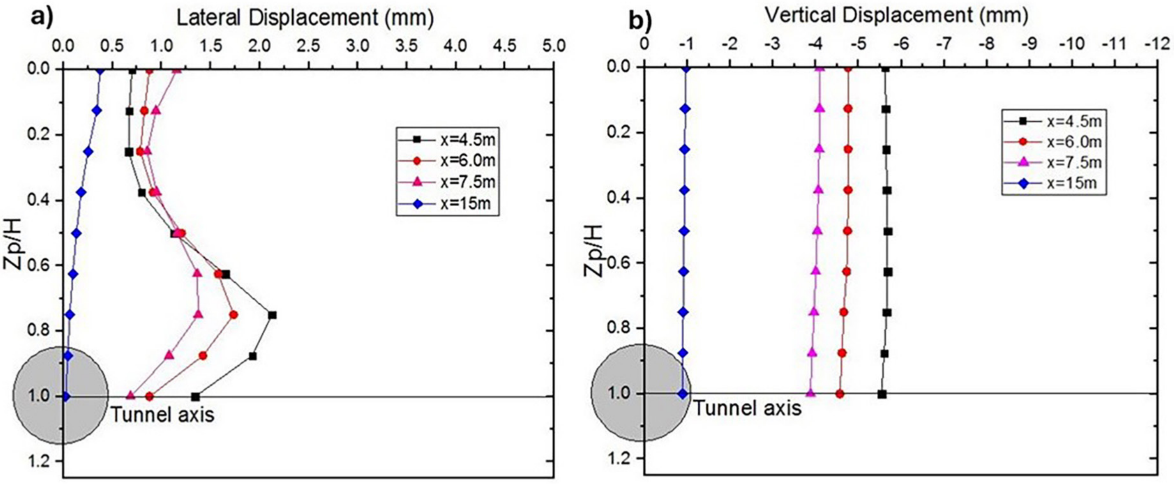

Figure 19: Pile at different horizontal distance 'x' from tunnel centerline in medium dense sand. (a) lateral displacement; (b) vertical displacement.

and 1.2 mm. Except for the pile at a distance x = 15m from the tunnel centreline, uniform vertical displacement was observed all along the depth of the pile located at the other three locations. The vertical displacement of the pile at x = 15 m was decreased gradually from 1.2 mm to 0.9 mm, from pile head at surface level to pile tip at tunnel axis respectively. A similar analysis was carried out in medium-dense sand to study the effect of varied distances between the tunnel and the pile. From Figure 19 (a), it was observed that the profile of lateral displacement of pile located at different distances x = 4.5 m, 6.0 m, 7.5 m, and 15 m were like in loose sand. However, due to increased soil parameters, the lateral displacement values obtained at the ground surface and pile depth 0.75H (i.e., depth of maximum response) for different pile distances x = 4.5 m, 6.0 m, 7.5 m, and 15 m were lesser than in loose sand such as 0.69 mm, 0.87 mm, 1.15 mm and 0.37 mm and 2.12 mm, 1.73 mm, 1.37 mm, and 0.06 mm respectively.

From Figure 19b, it was observed that the profile of vertical displacement of pile located at different distances x = 4.5 m, 6.0 m, 7.5 m, and 15 m from the tunnel centreline were similar as in loose sand. However, the values were lesser than in loose sand such as 5.6 mm, 4.7 mm, 4.1 mm, and 0.9 mm respectively due to increased soil parameters. The conservative value of 10 mm and 5 mm was considered for vertical and lateral displacement respectively. Though the lateral displacement for all the pile location from 4.5 m to 15 m from the tunnel centreline was less than 5 mm, the vertical displacement of the pile located at distance x = 4.5 m in loose sand was observed as 10.1 mm. Henceforth for further parametric studies, the pile responses were examined for the distance of the pile located at x = 4.5 m from the tunnel centreline.

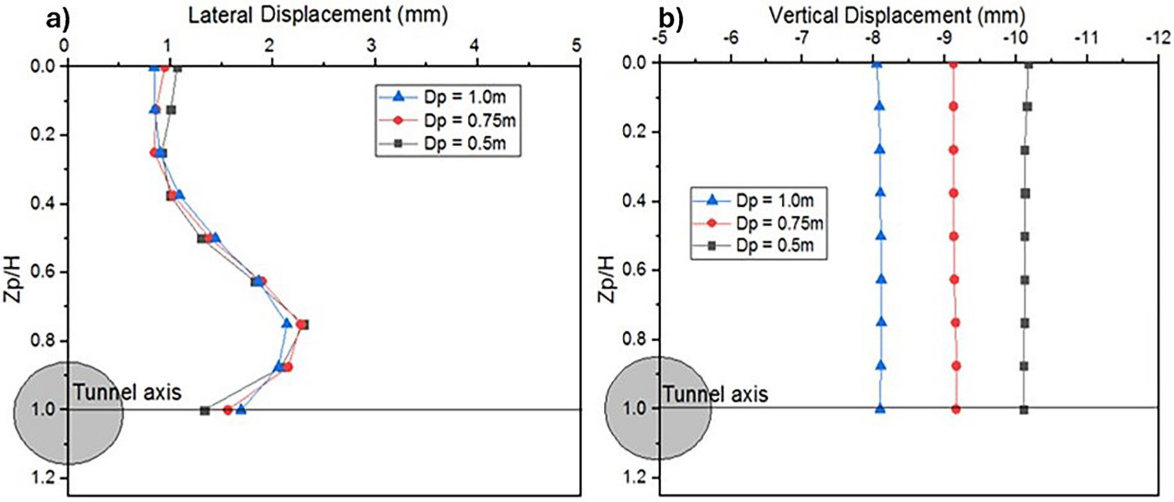

Figure 20: Different pile diameter in loose sand. (a) lateral displacement; (b) vertical displacement.

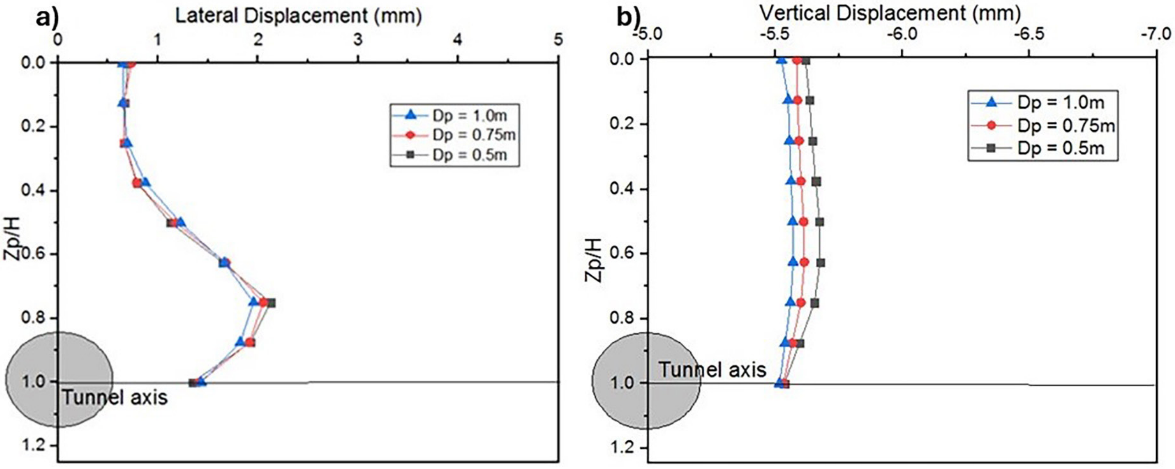

Figure 21: Different pile diameter in medium dense sand. (a) lateral displacement; (b) vertical displacement.

4.4. Effects of pile diameter

The effect of pile diameter was studied by analyzing the pile of different sizes, Dp = 0.5 m, 0.75 m, and 1.0 m located at the distance x = 4.5 m from the tunnel centerline. From Figure 20a it was observed that the varied diameter of the pile in loose sand had a negligible difference on the lateral displacements. From the ground surface up to the pile depth of 0.4H, the lateral displacement of three different pile diameters was around 1 mm and increased gradually around 2 mm at the pile depth of 0.75H. It decreased to around 1.5 mm at the tunnel axis. From Figure 20b it was observed that the vertical displacement of pile was 10.1 mm, 9.1 mm and 8.0 mm for diameter of pile Dp = 0.5 m, 0.75 m, and 1.0 m respectively. Hence it was indicated that the increase in rigidity of the pile above 0.5 m had decreased vertical settlement less than 10 mm.

The lateral and vertical displacement of the pile obtained for varied pile diameter D_p = 0.5 m, 0.75 m and 1.0 m in medium-dense sand is shown in Figure 21a and 21b respectively. From Figure 20a it was observed that the lateral displacement of the pile for varied pile diameters, D_p = 0.5 m, 0.75 m, and 1.0 m in medium sand was like the responses observed in loose sand and had negligible difference between the varied pile diameters. From the ground surface up to the pile depth of 0.4H, the lateral displacement of three different pile diameters was around 0.7 mm and increased gradually to around 2 mm at the pile depth of 0.75H. It decreased to around 1.4 mm at the tunnel axis. From Figure 21b it was observed that the vertical displacement of pile for varied pile diameters, D_p = 0.5 m, 0.75 m and 1.0 m was nearly the same with less difference such as 5.62 mm, 5.58 mm, and 5.52 mm respectively and in addition the same value 5.53 mm was observed at the tunnel axis. Hence it was indicated

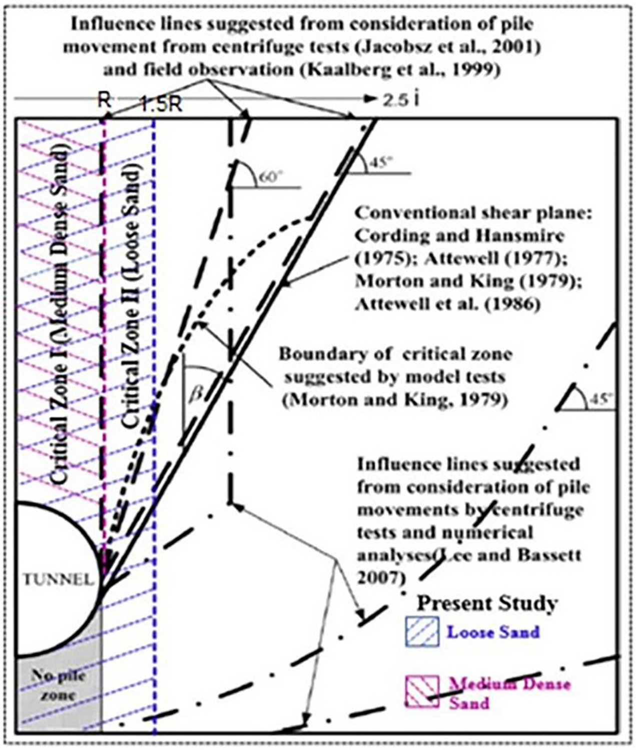

Figure 22: Critical zone of pile integrated with previous studies.

that the increase in rigidity of the pile in the increased soil parameters had an insignificant effect on both lateral and vertical displacements.

4.5. Key observations on pile responses due to tunnel excavations

Parametrical studies were carried out to understand the effect of various factors such as soil type, pile location, pile diameter, pile length, and volume losses on the pile displacement responses due to tunnel excavation. A general observation was increased soil parameters, a distance of pile from tunnel centreline, 'x', pile diameter, 'D_P' and pile length, 'L_P' had decreased displacement responses. However, the volume loss, V_L was directly proportional to the pile displacement responses. For all the cases, the lateral displacement of pile increased gradually from the pile depth, Zp = 0.4H to 0.8H, and then decreased towards the tunnel axis. The specific inward movement of the pile towards the tunnel especially at the depth above the tunnel axis was due to the soil arching which was most common in the deep-buried depth of tunnels [23]. The effect of soil arching was one of the functions of strength parameters, which mainly affects the vertical stress distribution, especially in the tunnel front [24]. Since the pile is a rigid body, uniform vertical displacement was observed along the pile depth from pile head to the pile tip. However, in some cases, the vertical displacement of the pile had decreased at the tip level, due to the rotation of soil near the tunnel displaced the pile along with it. Based on the safe limiting value of lateral displacement and vertical displacement as 5 mm and 10 mm respectively, it is suggested that the tunnel centreline could be located at a distance not less than 1.5 times the radius of the tunnel from the adjacent existing piles of diameter not less than 0.5 m. Therefore, the volume loss which is less than or equal to 0.5% is the maximum safe limit for all types of sand especially in the congested areas of the tunnel near the deep foundation system.

4.6. Influence zones of pile

Critical Zones I and II are shown in Figure 22 are suggested as the influencing distance of pile foundation from the tunnel centreline in medium dense as R and loose sand as 1.5R respectively for a volume loss of 0.5%. These critical zones were compared with the critical or influencing zone suggested for consideration of pile movements from previous studies and found well agreed with the influence lines suggested by [13, 25]. In addition, grout pressure control is suggested for the pile in this influencing zone to prevent the rotation of the pile, especially near the tunnel axis.

5. CONCLUSIONS

Based on the parametrical studies carried out in this research to examine the characteristics of the pile or pile group foundations, it was commonly observed that the lateral displacement of the pile increased gradually from the pile depth Zp = 0.5H to 0.8H and then decreased towards the tunnel axis. The specific inward movement of the pile towards the tunnel especially at the depth above the tunnel axis denotes the effect of soil arching which is most common in the deep buried depth of the tunnel.

By adopting the safe limiting value of lateral displacement and vertical displacement as 5 mm and 10 mm respectively, it is suggested that the tunnel centerline could be located at a distance not less than 1.5 times the radius of the tunnel from the adjacent existing piles of diameter not less than 0.5m. Critical Zones I and II are recommended as the effective influence distances between the pile foundation and tunnel centerline. R represents the distance in medium-dense sand and 1.5R in loose sand, corresponding to a volume loss of 0.5%. The volume loss of less than or equal to 0.5% is recommended to be the maximum safe limit for all types of sand especially in the congested areas of the tunnel near the deep foundation system. The recommendations are provided for varied tunnel & soil parameters and critical zone for pile distance from tunneling during excavation. It serves as a guideline to the geotechnical engineers and site engineers to align the tunnel especially in sands with utmost consideration in the nearby pile foundations without any disturbances. It is highly recommended to execute the tunneling activities at a distance away from the existing pile foundation based on the influence zone. Under unavoidable circumstances, necessary actions such as alteration of grout pressure and preventing excess volume loss shall be prearranged to minimize the impact on the existing foundation system due to tunneling within this influence zone.

6. SCOPE FOR FUTURE WORK

The influence zones will have significant changes for heterogeneous ground conditions. The soil is supposed to follow the elastic-plastic stress-strain relationship and obey the Mohr-Coulomb failure criterion. The Mohr-Coulomb material model cannot be used to capture the nonlinear, inelastic, and stress-dependent behaviour of soil. However, the parameters of the Mohr-Coulomb model were often used for pile-tunnel interactions, especially in sand. The effect of advanced soil models may be incorporated in the extension of further research. Verification of results accounting for the simulations using statistical methods has significant effect on research. Drained analysis was carried out for all the cases, however, alteration in the water table would have a significant effect on the responses. In addition, if the pile geometry and material properties are altered, significant changes in displacement behaviour would occur.

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