Pile Response Due To Tunnelling Induced Ground Movements

I.M.G.S.P Bandara[1] ,C.K.P.C Kumara[2],R. Nishanthan[1]
[1,2,3]Department of Civil Engineering, Faculty of Engineering, University of Jaffna,
[1]dasunsudeep@gmail.com

Abstract: The research thoroughly examines the profound impact of tunnelling-induced ground movements on the behaviour and stability of adjoining pile foundations. Employing advanced numerical analysis with the PLAXIS 2D software, this investigation methodically examines how tunnel diameter, depth, position, and diverse soil types decisively shape the response of pile foundations in the face of such ground movements. Through systematic parametric studies, comprehensive design charts were constructed to systematically anticipate pile behaviour across diverse scenarios. This encompassed an in-depth evaluation of soil settlement, pile deformation, axial load exertion on the piles, and the bending moments endured by the piles, across varying soil types, pile group positioning, distances from the tunnel central axis, and tunnel dimensions. The research reveals a direct link between soil settlement, stresses, tunnel dimensions, and pile types. Additionally, pile deformation, end reactions, and bending moments were assertively shown to be notably affected by these critical variables. Notably, the study distinctly highlights the amplification of settlement in conjunction with the ratio of the distance from the tunnel top to the ground surface relative to the tunnel diameter.

Keywords: Pile Response, Tunnels, Numerical Analysis.

Introduction

Tunnels constitute critical infrastructure components, serving diverse construction needs, including railways, roadways, and pipeline installations. The growing global population necessitates the expansion of underground infrastructure, driven by escalating demands for transportation networks, as well as water and sewage management systems. Consequently, the increase in population density is a significant factor contributing to the reliance on and development of underground infrastructures [1].

The type of foundation, the characteristics of the soil beneath the foundation, and the foundation's dimensions are critical factors influencing the stability of adjacent structures. Additionally, soil movement plays a significant role in determining the overall stability of a structure.

Ground movements induced by tunnelling activities have varying impacts on the behaviour of pile foundations. Such activities result in stress relief in the adjacent soil, consequently leading to further movements and imposing additional loads on existing pile foundations [2].

Current research indicates that soil displacement resulting from tunneling activities induces a reduction in soil friction along the pile shaft, which in turn decreases the axial load-bearing capacity of the piles [3]. Moreover, the extent of lateral deflection experienced by piles is influenced by several factors, including the lateral distance between the tunnel's central axis and the pile, the depth of the tunnel, the tunnel's diameter, and the properties of the surrounding soil [4].

The excavation of tunnels induces soil displacements which have a consequent impact on the structural integrity of piles. Before the initiation of any tunnelling activities near infrastructural elements of critical structures, such as high-rise buildings, a comprehensive examination of soil movements must be undertaken. To facilitate an in-depth understanding of the pile behaviour in response to tunnel-induced ground displacements, the development of a sophisticated model is necessary. Such a model would serve to diminish the potential adverse effects on surrounding structures, thereby ensuring their stability and safety.

Methodology

Selecting a suitable method

Several methods are available for analyzing research such as empirical method, analytical method, experimental method, and numerical method. The empirical method doesn't give highly accurate results and its applicability to different ground conditions and construction techniques is less [3]. The analytical method is more suitable than available empirical methods. Most of researchers have done with the analytical methods. Interaction between surrounding structures, ground heterogeneity can't be included. Analytical solutions require no site-specific calibration of the material behavior [3].

When considering the experimental methods such as centrifuge test, energy consumption and initial capital loss are high. The numerical method is a more appropriate method for the estimation of pile response due to tunnelling-induced ground movements. Effects of the soil movement, ground heterogeneity, soil nonlinearity, and complex tunnel geometries can be considered during numerical methods. A finite element tool is needed for the analysis and PLAXIS 2D computer software was chosen as the analyzing tool.

Finite element modelling

Plaxis2D was used for 2D modelling of pile response due to tunnelling-induced ground movements. Plane-strain condition was considered. Modelling parameters such as contraction, and strength reduction factors were defined before modelling. In this research, circular tunnel was considered. Therefore, contraction value is considered as 0.5% in 2D modelling. Because average volume loss of circular tunnel is 0.5%. Strength reduction factor was obtained as 0.7 in deep clay and deep sand for indicating strength reduction in soil-structure interface.

Pore water pressure distribution profile was assumed to be hydrostatic.Tunnel lining is assumed to be impervious. For stiff clay, the strengthparameters are assumed as follows: effective cohesion (c') of 5 kPa, effective angle of friction (ϕ') of 20°, and angle of dilation (ψ) of 11°. The stiffness parameters are considered anisotropic and increase linearly with depth. The concrete piles, pile cap are assumed to behave as linear elastic materials, with a Young's modulus of 35 GPa and a Poisson's ratio of 0.25 [5].

The behaviour of the tunnel lining is assumed to be governed by a linear-elastic relation with a Young's modulus E=35 000 MPa and a Poisson's ratio n = 0.25. The axial and bending stiffnesses of the lining are equal to Ksn=4978 MPa and Ksf=7.4 MN m^2. The soil behaviour is supposed to be governed by an elastic perfectly-plastic constitutive relation based on the Mohr–Coulomb criterion [5].

In this study, the tunnel diameter (D) is assumed to be 6 meters, with varying cover depths (C) of 12m, 15m, and 18m. The model includes a pile group consisting of four piles (2× 2 configuration), spaced at 2.5m center-to-center. Each pile is 19m long, with 1m of the pile extending above the ground surface and has a diameter of 0.8m. The pile group is positioned at 5.5m from the tunnel centerline, exploring the impact of varying cover depths on structural performance [5].

The specified configuration underwent multiple iterations of modeling across various soil typologies, encompassing sand, clay, deep clay, and deep sand. Because pile response is depended with soil type [3]. The investigation focused on both grouped and singular pile configurations to deduce the pile response. Comprehensive analyses were executed, and responses were distinctly derived for each pile within the grouping.Specifically, a 2× 2 pile group configuration was chosen for this study.

Validation

The study undertaken by Soomro et al. (2014) was selected as the case history [5]. Model values were compared with field monitoring data of the case history. Validation was completed with minimum error (0% -6% range deviation in settlement). The 0% to 6% error range indicates generally reliable model predictions, though discrepancies may arise from assumptions, parameter inaccuracies, and boundary condition mismatches.

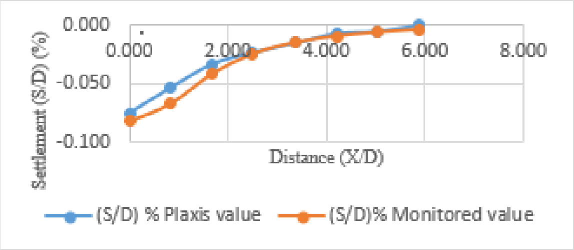

Figure 1: Model validation with monitored values

Parametric studies with design charts

Parametric studies were done for single and group piles. The settlement of the soil, pile deformation, axial load of the pile, and bending moments of the pile were estimated by changing the position of the pile with respect to the tunnel, the position of the pile in the group, the distance between the pile and tunnel center axis, and tunnel dimension. Different soil type were used for the parametric studies such as clay, sand, dense sand, stiff clay. With the aids of outcomes of the parametric studies, design charts were developed to represent pile response.

Results & Discussion

Pile response variation with pile type

The ability of reaction against loads is differed according to the pile type as shown in Fig 2. Therefore, pile response is varied according to pile type. Clay soil is selected as the soil type for analyzing the variation of soil settlement. Material type and dimensions were same in single pile and each pile of the pile group.

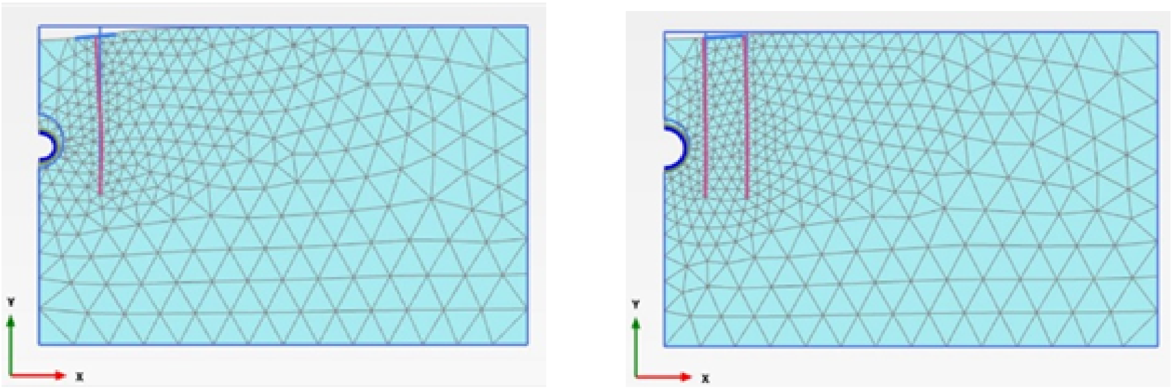

Figure 2: Pile response variation with pile type

Pile response variation with soil type

Settlement is high at below the pile. When distance from pile is increased, settlement is decreased gradually as shown in Fig 4. And settlement is depended on soil type. Clay soil shows highest settlement when compared to other soil types.

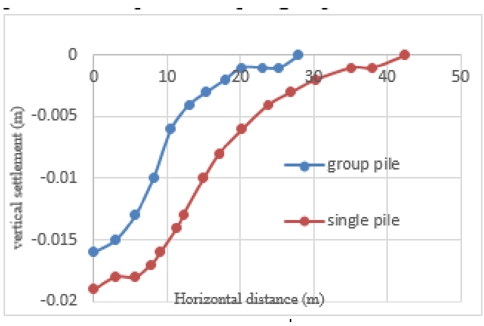

Figure 3: Pile settlement variation with pile type

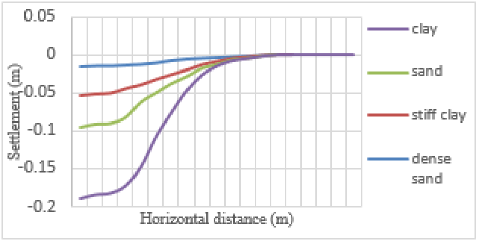

Figure 4: Soil settlement variation with soil type

Pile response variation with tunnel position

Fig. 5 shows how the pile response is changed with the tunnel position. When the tunnel position goes more deeper, soil loads which effects on the tunnel are high. Therefore, the soil settlement increases with the depth of the tunnel. C is the distance between tunnel top and ground surface. D is the tunnel diameter. If C is increased while tunnel diameter is constant, settlement is changed according to C/D ratio.

Pile response variation with tunnel diameter

When tunnel diameter is increased, volume loss of the tunnel increases. It causes for increasing the maximum bending moment, pile settlement, compressive axial force.

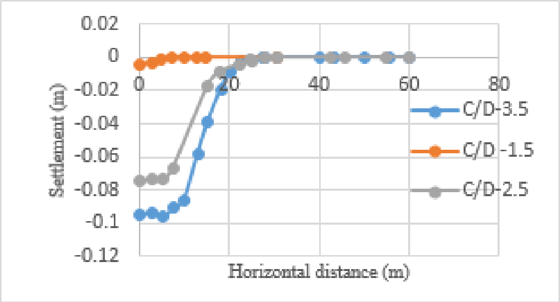

Figure 5: Pile settlement variation with tunnel location

Conclusions & Recommendations

Soil settlement is varied according to the soil type. Soil type is affected for pile deformation. Axial force of pile is higher at sand when compared with clay. This increment is approximately 250% at the bottom of pile. Bending moment of pile is varied along the pile.Highest bending moment is at top of the pile.

Ability of reaction against loads is differed according to the pile type. Group pile shows less settlement than single pile for the same load and same configuration. In this scenario, single pile shows a settlement of 20% extra than group pile in clay soil. When 2× 2 group pile is considered, pile which is closer to the tunnel deforms more than other pile. That increment is approximately 150%. When tunnel go deep, settlement of the tunnel is increased. Settlement is increased with C/D ratio where C is the distance between tunnel top and ground surface, and D is the tunnel diameter. When tunnel diameter is increased, soil settlement increases with it because of high volume loss.

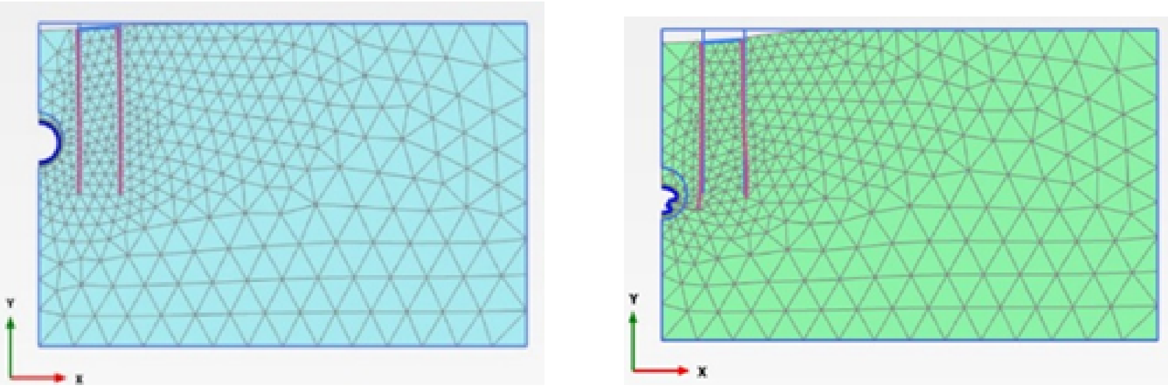

Figure 6: Pile settlement variation with tunnel position

Soil type, tunnel diameter, depth, and position affect pile response by altering soil displacement and stress. Larger diameters and greater depths increase ground settlement and pile stress, while piles closer to the tunnel experience more deformation. Engineers use finite element models and real-time monitoring to manage these effects and prevent structural damage. Without proper management, significant structural instability and remediation costs can arise. In addition, in dense urban areas, larger and deeper tunnels require advanced stabilization to manage significant ground movement, while in softer soils, greater effects are seen due to soil compressibility. Adapting practices to local conditions is essential for maintaining structural integrity.

Acknowledgment

The authors would like to extend their gratitude to University of Jaffna for providing the necessary guiding for this research through URG/2018/SEIT/09, to the Department of Civil Engineering, University of Jaffna for the generous support.

References

[1] Lee, C.-J, “Ground movement and tunnel stability when tunneling in sandy ground,” *Journal of the Chinese Institute of Engineers*, vol. 27, pp. 1021–1032, 2004.

[2] Basile, F, “Effects of tunneling on pile foundations,”*Soils and Foundations*, vol. 54, pp. 280–295, 2014.

[3] Poulos, H.G, “Pile responses caused by tunneling,”*Journal of Geotechnical and Geoenvironmental Engineering*, vol.125, no. 3, pp. 207–2015, 1999.

[4] Shahrour, H.M. and Shahrour, “Three-dimensional finite element analysis of the interaction between tunneling and pile foundations,”*International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 26, no. 3, pp. 217–230, 2002.

[5] Soomro, M.A, “3D numerical analysis of the effects of an advancing tunnel on an existing loaded pile group,” *Engineering,Technology & Applied Science Research*, vol. 8, pp. 2520–2525, 2018