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EVALUATION THE BEHAVIOR OF PULLOUT FORCE AND DISPLACEMENT FOR A SINGLE PILE: EXPERIMENTAL VALIDATION WITH PLAXIS 3D

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ABSTRACT

This study conducted an experimental and numerical investigation to examine the pullout behavior of a single pile in sand soil with a specific density. The soil testing model was constructed to simulate real-world geotechnical applications where the soil is subjected to varying pullout forces. The experimental setup involved measuring vertical displacement corresponding to different values of pullout forces. The results were then compared to numerical results obtained from a PLAXIS 3D model with HS-small. The experimental and numerical results showed good agreement, demonstrating the effectiveness of the numerical model in simulating real-world geotechnical applications. The study provides valuable insights into the pullout behavior of a pile in soil with specific density and can be used to improve the design and construction of geotechnical structures. The difference between experimental results and numerical predictions was in acceptable values.

KEYWORDS: Pullout force, Steel Pile, FEA, Sandy soil, Plaxis 3D.

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1. INTRODUCTION

A foundation is the base or lowermost part of a building or structure that is in direct contact with the ground and supports the weight of the building (Allen and Iano, 2019). The soil layers receiving the loads must be strong and not easily compressible to prevent soil shear failure and excessive settling (Mohamad *et al.*, 2016; Yusof and Zainorabidin, 2022). Various types of foundations are chosen based on factors such as water table location, superstructure weight, soil conditions, cost, and materials availability. Generally, foundations are divided into two categories: shallow foundations, used when the top soil below the structure is strong enough to support it, and deep foundations, used to transfer loads to deeper layers when the upper soil is not firm (Dashti et al., 2010). Deep foundations usually extend much deeper into the soil than their width. This category encompasses various types, including piles (Aziz and Abdallah, 2018), drilled shafts, piers, and caissons. Piles, made of concrete, steel, timber, or composite materials, are the most commonly used type of deep foundation and are applied in traditional buildings, tall structures, bridges, towers, etc. They are defined as structural members that transfer loads into the soil (Prakash and Sharma, 1991). Piles are primarily employed to withstand vertical compression, uplift, and horizontal or inclined loads (Spagnoli and Tsuha, 2020; Malhotra and Singh, 2022). They are utilized to counteract uplift loads in bridge foundations, abutments, and tall structures subject to overturning loads from environmental factors such as wind and waves.

Additionally, piles can minimize settlement (Shukla, 2020) by positioning their tips above soil layers with high compressibility. The pile's self-weight and skin friction along its surface offer resistance against uplift forces (Reddy and Ayothiraman, 2015). Recently, there has been a significant rise in the construction of transmission towers, high-rise buildings, and tall structures. The foundation system must also be capable of resisting vertical uplift forces to meet the design requirements of these engineering structures (Kranthikumar, 2016). Geotechnical engineering has utilized piles or pile foundations for numerous years to transfer and bear loads onto soils that are perceived to have a weak structure owing to their conditions. Nazir and Nasr carried out a model of a steel pipe pile in loose, medium, and dense sand, with varying embedded lengths and batter angles, to examine the impact of different parameters on the ultimate pullout load capacity of a battered pile. According to the findings, a battered pile constructed in dense and medium sand has a higher ultimate pullout capacity when the batter angle increases. The ultimate pullout capacity decreases in loose sand as the pile batter angle increases.

Additionally, an increase in the embedment ratio and relative density of sand results in a higher ultimate pullout capacity (Nazir and Nasr, 2013; Fakher and Fakhruldin, 2021). The estimation of soil deformation surrounding the pile is crucial for ensuring the reliable design of structures against pullout force, as emphasized by Faizi et al., (2015). They confirmed the laboratory test outcomes using finite element method software, revealing that soil deformation is associated with density and depends on its dilatancy. Lozovyi and Zahoruiko, (2014), used a finite element program to conduct four static pile tests and calculate pile settlements. The results were then compared to full-scale pile tests to determine the impact of reaction piles on the test pile's response. To investigate this, simulations were conducted with a group of reaction piles surrounding the tested pile and applying respective negative loads. A strong correlation existed between the load-displacement curves obtained through in situ measurement and those obtained using Plaxis. Furthermore, suggestions were provided for enhancing the Plaxis modeling. This paper uses a finite element model in Plaxis 3D Alasadi and Mustafa, (2022) to simulate the behavior of a single pile in sandy soil under pullout force using experimental data for validation from a real case study.

2. FINITE ELEMENT MODELLING

PLAXIS-3D is used to simulate the behavior of piles under uplift forces due to its advanced capabilities in modeling complex soil-structure interactions. It can accurately account for factors such as soil type, pile geometry, and boundary conditions, making it a powerful tool for analyzing the response of piles to uplift loads. Using PLAXIS-3D, engineers and researchers can predict the behavior of pile foundations under different uplift loads and assess the structural integrity of the foundation system. They can also evaluate the effectiveness of various design strategies and determine the optimal pile configuration to ensure stability against uplift forces. Overall, the use of PLAXIS-3D in simulating the behavior of piles under uplift forces enables a more precise and comprehensive understanding of the behavior of foundation systems, ultimately leading to more robust and effective engineering designs.

2.1. Hardening Soil model with small-strain stiffness (HS_{small})

The Hardening Soil model with small-strain stiffness (HSsmall) model is a popular choice for simulating soil behavior in Plaxis because it provides several advantages over other soil models. Here are some of the reasons why the HSsmall model is commonly used:

- Accurate representation of soil behavior: The HSsmall model is based on the Hardening Soil model, a popular constitutive model used to simulate the mechanical behavior of soils.

The HSsmall model incorporates small-strain stiffness, which enables it to accurately represent the behavior of soils under cyclic loading and dynamic loading conditions.

- Improved performance under large deformation: The HSsmall model is better equipped to handle large deformations than other soil models, making it a valuable tool for simulating the behavior of soil during tunneling Hilar, (2011), excavation Saplachidi and E. Vougioukas, (2018), and other activities that involve significant soil displacement.
- Increased reliability: Compared to the HS model, the HSsmall model provides more reliable results, particularly regarding displacement predictions.
- Compatibility with Plaxis software: The HSsmall model is implemented in the FEA, making it easy for engineers and researchers to incorporate it into their simulations.

HSsmall is an updated version of the Hardening Soil model that addresses the heightened stiffness of soils at small strains. Typically, soils display greater stiffness at low strain levels than at engineering strain levels, and this stiffness varies non-linearly with strain. The HSsmall model captures this phenomenon by introducing two new material parameters and an additional strain-history parameter, i.e., G^{ref}_0 and γ_{70} . G^{ref}_0 refers to the small-strain shear modulus, while γ_{70} is the strain level at which the shear modulus has reduced to approximately 70% of the small-strain shear modulus. The HSsmall model's enhanced capabilities are particularly noticeable when operating under working load conditions, as it produces more dependable displacements than the HS model.

Moreover, utilizing the Hardening Soil model's small-strain stiffness in dynamic scenarios results in the additional benefit of introducing hysteretic material damping. Overall, the HSsmall model is a valuable tool for simulating soil behavior in a wide range of scenarios. Its accuracy, reliability, and compatibility with Plaxis make it a popular choice for soil analysis.

2.2. Pile Modelling in Finite Element FEA

Embedded beams are appropriate for certain pile types that cause minimal disturbance to the surrounding soil during installation. These may include specific bored piles like displacement screw piles, but not most replacement piles or displacement piles technologies (*PLAXIS 3D*, 2020). In Plaxis (Hilar, 2016), modeling a pile as an embedded beam can help simulate the pile-soil system's behavior. It can provide improved accuracy. This is because the embedded beam approach can better account for the interaction between the pile and the surrounding soil, which can be critical in accurately simulating the behavior of the pile-soil system. In addition, the simulation of a pile as an embedded beam can also provide greater control over modeling parameters, such as the stiffness and strength of the pile and the soil. This can help ensure that the simulation accurately represents the actual behavior of the analyzed system.

3. EXPERIMENTAL SETUP

The testing model is a container consisting of a steel box measuring $50 \times 50 \times 150$ cm, as shown in Fig. 1. The height of the steel container was adjusted to accommodate the length of the model pile. A steel loading frame was fabricated to support the axial loading system and apply dead loads to the model pile. The pullout load is transmitted to the model pile by a flexible steel cable with a diameter of 6 mm. A steel base was created to uphold the weight of the container and loading frame. The container was positioned between two steel channels secured to the base, preventing any sideward displacement of the frame. The steel pile used in the experimental work is about a 60 cm long pile with a 5 cm diameter. To simulate the pile within the foundation soil, a soil density of 15.67 kN/m^3 and friction angle values (φ) of 41^0 were used (Hamadi and Abdul-Husain, 2021; Hamadi and Abdul-Husain, 2021). Seven case studies were performed using this instrument, for each case study single pile was inserted in the box then soil around it was compacted to the desired density. Loads were applied to the pile cap and corresponding vertical displacement were measured using dial gauge.

Fig. 1. Pullout force measuring instrument.

4. NUMERICAL MODELLING

The sandy soil properties used in the numerical model are summarized in Table 1, and

Table 2 illustrates the input parameters of the pile used in the FEA model.

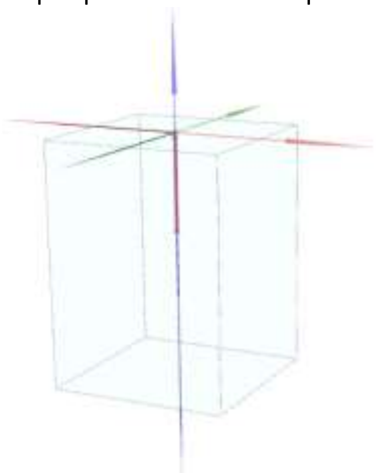

Fig. 2 shows the 3D model for the single pile used in this study.

Table 1. Properties of sand soil used in the FEA model.

Parameters	Name	Unit	Value
Model of material	HS small	-	-
Drainage type	Type / Drained	-	-
Unit weight of sand	γ_{dry}	kN/m^3	15.67
The stiffness of the tangent during primary oedometer loading.	E_{od}^{ref}	MN/m^2	15
The stiffness of the secant in a standard drained triaxial test.	E_{50}^{ref}	MN/m^2	15
Stiffness during unloading and reloading	E_{ur}^{ref}	MN/m^2	45
The relationship between power and stress-level dependence of stiffness.	m	-	0.5
Cohesion	c'_{ref}	kN/m^2	0
Angle of dilation	ψ	^{o}	1
Angle of internal friction	φ′(phi)	^{o}	41
The level of shear strain when the shear modulus is reduced to 70%, as observed in HSsmall only	γ_{70}	-	0.17*10^{-3}
Shear modulus at a reference state	G_0^{ref}	KN/m^2	75*10^3
Poisson's ratio	v'_{ur}	-	0.2
Reference stress for stiffnesses	p^{ef}	KN/m^2	100
K_0-value for normal consolidation	k_0^{nc}	-	0.35
Interactional strength reducing factor	R_{inter}	-	0.8

Table 2. Properties of steel pile used in the FEA model.

Parameters	Name	Unit	Value

Material type	Elastic	-	-
Young's modulus	*E*	KN/m^2	200*10^6
Unit weight	γ	KN/m^3	78
Diameter	D	Cm	0.5

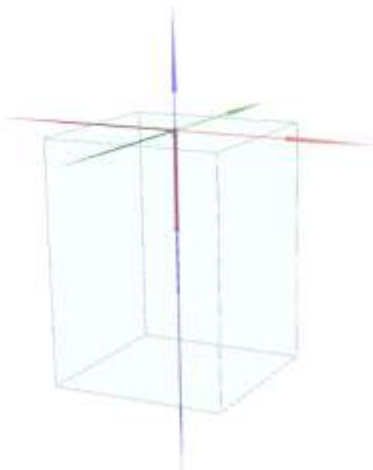

Fig. 2. Plaxis 3D model of a single pile.

Table 3 shows seven experimental case studies estimating the pullout force of a single pile, and shows the difference between the experimental and numerical results.

Table 3. Validation of numerical and experimental data of pullout behavior with difference between observations.

Pullout force kN/m^2	Experimental, mm	Numerical, mm	Difference, mm
0	0	0	0
0.025	0.027	0.02671	0.0003
0.20654	1.117	0.96	0.1570
0.2295	1.184	1.26	0.0760
0.3209	2.318	2.059	0.2590
0.388	7.927	6.58	1.3470
0.40845	19.725	21	1.2750

Fig. 3 shows the first state of the numerical analysis, representing the pile as an embedded beam subjected to zero loads. Upon comparing the experimental results based on an actual case study with results from the FEA, we observed a very satisfactory level of difference between the two sets of results, as illustrated in Fig. 4, while Fig. 5 illustrates the deformation versus depth for the pile model.

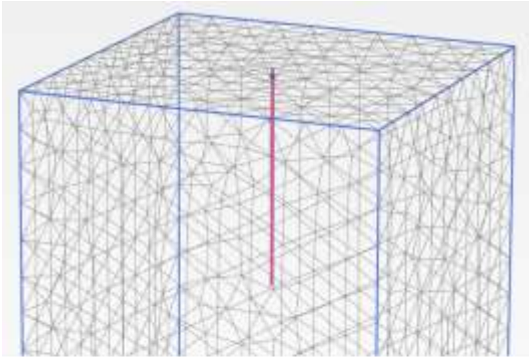

Fig. 3. Pile subjected to zero loads in the FEA model.

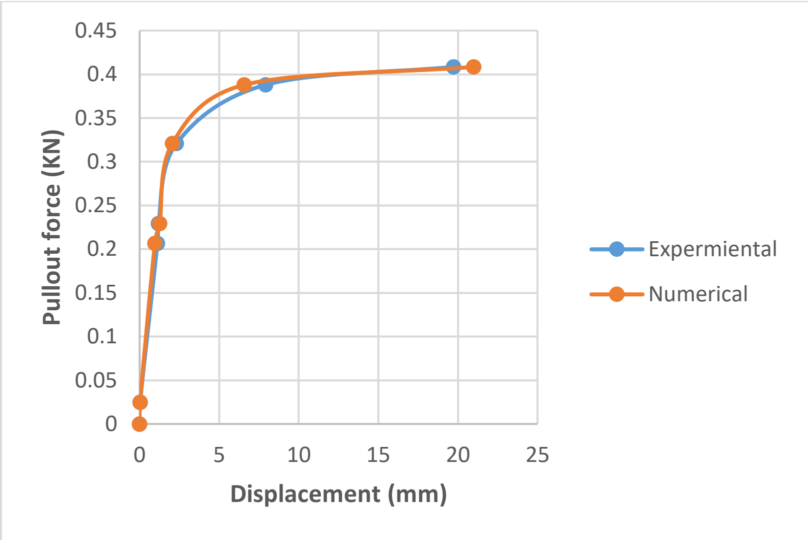

Fig. 4. Experimental and Numerical Results.

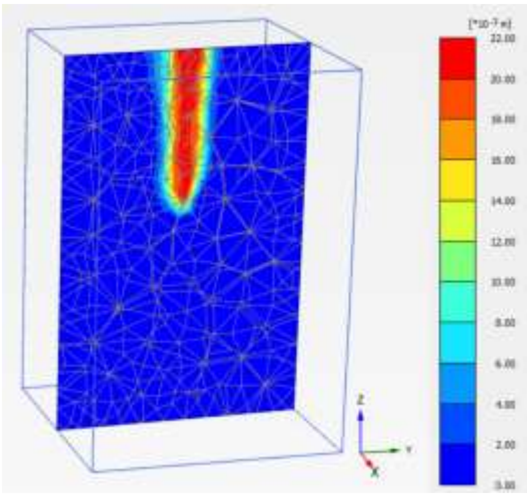

Fig. 5. Deformation of the pile in the vertical plane.

Fig. 6 illustrates the failure points in the pile, which PLAXIS typically identifies as the location where the pile's maximum resistance capacity is reached, and it begins to experience significant plastic deformation or even ultimate failure. This information can be crucial in determining the suitability of a pile design and assessing the potential risks associated with the failure of the pile under extreme loading conditions

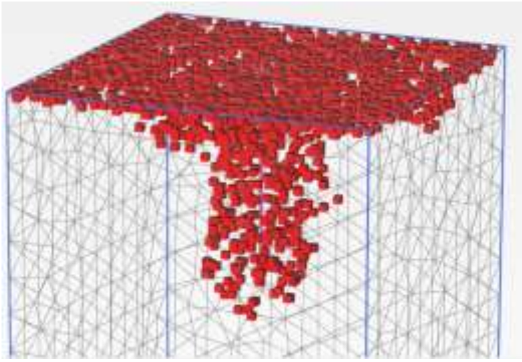

Fig. 6. Failure points in the soil due to pile extraction.

Fig. 7 shows the tension cut-off point resulting from a plastic point in PLAXIS, which represents the location where the soil's behavior transitions from plastic to elastic, and the stress-strain relationship changes from following the plastic curve to a more linear elastic curve. This information is essential in evaluating the stability and safety of soil structures, especially under high-stress loading conditions.

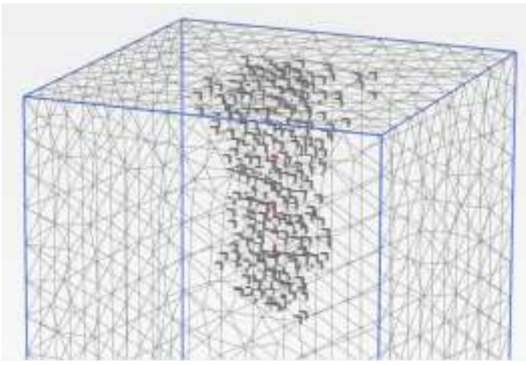

Fig. 7. The tension cut-off point resulting from a plastic point in FEA model.

Fig. 8 reveals the cap points that refer to the points on the plastic curve where the curve ends and becomes horizontal. The plastic curve represents the shear strength properties of soil under various loading conditions, and it is often used in numerical simulations to predict the soil's behavior under different loading scenarios. The plastic curve typically begins at the origin, where the shear stress is zero, and the shear strain is the elastic strain. As the shear stress increases, the soil begins to deform plastically. The curve follows a nonlinear path until it reaches a maximum point (known as the plastic limit or yield point) beyond which the soil can no longer deform plastically. After reaching the plastic limit, the curve flattens out and becomes horizontal, indicating that further increases in shear stress will not result in any additional plastic deformation. The points on this flattened portion of the plastic curve are called "Cap points." These points represent the soil's maximum strength under plastic deformation conditions. In PLAXIS, the Cap points are vital because they help to define the soil's strength properties, which are critical in evaluating the stability and safety of soil structures, such as retaining walls, slopes, and foundations. Knowing the location of Cap points on the plastic curve can also help optimize the design of geotechnical structures and predict the soil's behavior under different loading conditions.

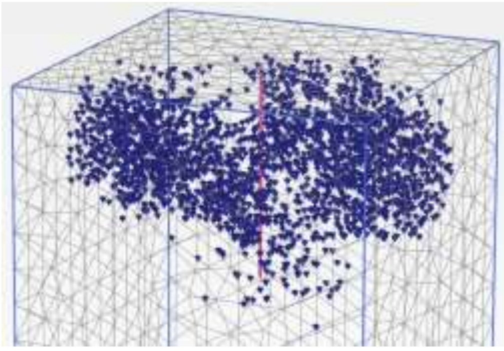

Fig. 8. Cap points representing the shear strength properties.

In PLAXIS, Cap + hardening points in a pile, as shown in Fig. 9, are typically identified by analyzing the pile's load-settlement curve. The Cap point marks the end of the pile's plastic phase, where the pile's resistance no longer increases with deformation. Beyond this point, the pile's resistance increases with further deformation, and the curve becomes horizontal. The hardening points refer to the locations where the curve begins to slope upwards again, indicating that the pile's resistance increases with further deformation. Identifying Cap+ hardening points is essential in evaluating the pile's behavior and determining its capacity to resist the applied load. This information can be used to optimize the pile design and ensure the stability and safety of geotechnical structures that rely on pile foundations, such as bridges, high-rise buildings, and retaining walls.

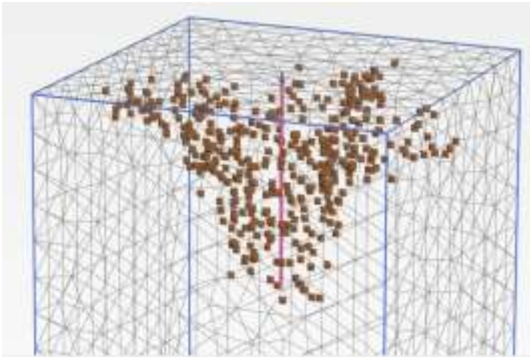

Fig. 9. Cap + hardening points representing pile's behavior and its capacity to resist load.

When a pile is subjected to a load, its resistance to the load can be divided into three distinct phases: elastic, plastic, and hardening. The elastic phase represents the initial response of the pile to the applied load, where the pile undergoes minimal deformation without significant changes in resistance. The plastic phase begins when the applied load exceeds the pile's yield strength, causing significant deformation without an increase in resistance. The hardening phase begins after the plastic phase, where the pile's resistance increases with further deformation, as shown in Fig. 10.

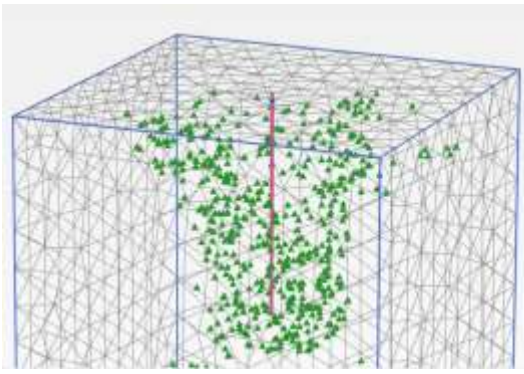

Fig. 10. Hardening points indication to the pile's resistance increasing with further deformation.

5. CONCLUSION

Based on the pullout force and displacement behavior for a single pile through experimental validation with Plaxis 3D, some points can be concluded.

- The numerical results obtained through FEA using Plaxis 3D have shown good agreement with the experimental results, indicating the validity of the simulation approach.
- The pile displacement due to pullout force can be accurately predicted using Plaxis 3D, with the model able to capture the behavior of the soil-pile interaction under different loading conditions.

- The validated numerical model can be used to design and analyze pile foundations, providing a cost-effective and efficient alternative to experimental testing.
- The difference between experimental results and numerical predictions were close to each other in an acceptable rage.

In summary, evaluating pullout force and displacement behavior for a single pile through experimental validation with Plaxis 3D has demonstrated the reliability and accuracy of numerical simulation for studying the behavior of pile foundations under different loading conditions and soil types.

6. REFERENCES

Alasadi A. A. and Mustafa F. S., "Numerical Analysis for the Response of Skirt Circular Shallow Footing Resting on Sandy Soil under vertical loads," *Kufa J. Eng.*, vol. 13, no. 2, pp. 16–27, 2022.

Allen E. and Iano J., Fundamentals of building construction: materials and methods. John Wiley & Sons, 2019.

Aziz L. and Abdallah M., "Suitable location of sheet pile under dam resting on sandy soil with cavity," Kufa J. Eng., vol. 9, no. 2, pp. 168–188, 2018.

Dashti S., Bray J. D., Pestana J. M., Riemer M., and Wilson D., "Mechanisms of seismically induced settlement of buildings with shallow foundations on liquefiable soil," J. Geotech. geoenvironmental Eng., vol. 136, no. 1, pp. 151–164, 2010.

Fakher N. and Fakhruldin M., "Experimental study of relative density effect on bearing capacity of sand reinforced with geogrid," Kufa J. Eng., vol. 12, no. 3, pp. 46–55, 2021.

Faizi K., Kalatehjari R., Nazir R., and Rashid A. S. A., "Determination of pile failure mechanism under pullout test in loose sand," J. Cent. South Univ., vol. 22, pp. 1490–1501, 2015.

Hamadi H. and Abdul-Husain H., "Effect Of Soil Density And Plug Characteristics On Behavior Of Single Pipe Pile Embedded In Cohesionless Soil And Subjected To Uplift Force," Kufa J. Eng., vol. 12, no. 3, pp. 1–11, 2021a.

Hamadi H. S. and Abdul-Husain H. A., "Influence of Geometry and Separation Walls on The Behaviours of Pull-out Pipe Piles Embedded in Sandy Soil," in IOP Conference Series: Materials Science and Engineering, 2021b, vol. 1090, no. 1, p. 12010.

Hilar M., "3D modelling of a tunnel re-excavation in soft ground," Acta Polytech., vol. 51, no. 3, 2011.

Hilar M., "Evaluation Of The Surface Settlement Above The Prague Metro Line A Extension Constructed By Two Shields," vol. 56, no. 6, pp. 448–454, 2016, doi: https://doi.org/10.14311/AP.2016.56.0448.

Kranthikumar A., Sawant V. A., and Shukla S. K., "Numerical modeling of granular anchor pile system in loose sandy soil subjected to uplift loading," Int. J. Geosynth. Gr. Eng., vol. 2, pp. 1–7, 2016.

Lozovyi S. and Zahoruiko E., “Plaxis simulation of static pile tests and determination of reaction piles influence,” arXiv Prepr. arXiv1411.0929, 2014.

Malhotra H. and Singh S. K., “Effect of load inclination on the uplift capacity of the granular anchor pile foundation in cohesive soil,” Arab. J. Geosci., vol. 15, no. 11, p. 1088, 2022.

Mohamad N. O. et al., “Challenges in construction over soft soil-case studies in Malaysia,” in IOP conference series: materials science and engineering, 2016, vol. 136, no. 1, p. 12002.

Nazir A. and Nasr A., “Pullout capacity of batter pile in sand,” J. Adv. Res., vol. 4, no. 2, pp. 147–154, 2013.

PLAXIS 3D-Reference Manual. 2020.

Prakash S. and Sharma H. D., Pile foundations in engineering practice. John Wiley & Sons, 1991.

Saplachidi A. and Vougioukas E., “Comparison Of Actual Ground Settlements In Tunnelling Excavation To Model Predictions,” Acta Polytech., vol. 58, no. 1, pp. 47–56, 2018.

Shukla R. P., “Pile Settlement Induced From Soil Movement Due To Breakdown Of Retaining Wall,” Acta Polytech., vol. 60, no. 4, pp. 338–348, 2020.

Spagnoli G. and Tsuha C. de Hollanda Cavalcanti, “A review on the behavior of helical piles as a potential offshore foundation system,” Mar. Georesources Geotechnol., vol. 38, no. 9, pp. 1013–1036, 2020.

Reddy K. Madhusudan and Ayothiraman R., “Experimental studies on behavior of single pile under combined uplift and lateral loading,” J. Geotech. geoenvironmental Eng., vol. 141, no. 7, p. 4015030, 2015.

Yusof N. N. M. and Zainorabidin A., “Soft Soil Improvement by using Bamboo Reinforcement,” Recent Trends Civ. Eng. Built Environ., vol. 3, no. 1, pp. 956–964, 2022.