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Numerical Analysis of Single Stepped Axially Loaded Pile

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***Abstract:** This study investigates the behavior of a single pile under axial loading in granular soil layers. The study aims to determine the impact of stepping on load settlement behavior and load transformation along the pile, as it relates to depth. The pile has a diameter (D) of 1m and a length (L) of 20m. For the stepped pile, the upper portion is half the length of the pile and the lower portion is the remaining half. The total length and volume of the pile are kept constant for both the single conventional pile and single stepped pile. In the analysis, the diameter of the upper portion of the stepped pile is reduced (stepped pile) by 0.1D to 0.3D, and the diameter of the lower portion is calculated accordingly. Also the load transformation with respect to depth of pile is studied. Based on numerical analysis, the single stepped pile outperforms the single conventional pile in load settlement behavior.*

***Keywords:** Stepped pile, load settlement behavior, axial force distribution, FEM.*

I. INTRODUCTION

Axially loaded piles are a commonly used foundation element in civil engineering for supporting heavy structures or transferring loads to deeper soil strata. These piles transfer the load primarily through end bearing or skin friction. The design of axially loaded piles depends on various factors, including the type of soil, pile dimensions, and the magnitude and distribution of loads. Piles can be made of different materials such as concrete, steel, and timber, and can be installed through different methods, including drilling, driving, or jacking. The behavior of axially loaded piles under different loading conditions is complex and depends on the interaction between the soil and pile. The analysis of pile behavior is essential for ensuring the stability and safety of structures built on them. Therefore, extensive research has been conducted to investigate the behavior of axially loaded piles in various soil types and loading conditions. This research has contributed to the development of reliable design methods for axially loaded piles, making them a widely accepted and cost-effective foundation solution.

The behavior of piles under tension and compression was investigated through full-scale tests, and the results were modeled using the CÉSAR-LCPC finite element calculation package. Two models were considered to represent the behavior of the soil: a perfectly elastic model and an elastoplastic model with hardening. To capture the behavior of the soil-pile interface, contact elements and a Coulomb friction criterion were used. A reset of the friction parameters improved the agreement between the numerical results and the measured load- vertical displacement curves. However, the calculated force distributions along the pile did not match the measurements, indicating that the simple law of friction used was inadequate to describe the actual variations in lateral friction. Further improvements are needed to refine the pile design models and accurately represent the soil-structure interaction, [1]. A finite element method-based elasticity model was developed to study the behavior of bored piles in stiff clay. This model accurately predicts the load capacity and load-deformation behavior of a single pile. The stress-strain curve obtained from undrained triaxial tests was approximated as trilinear. The model shows that a tension crack forms at the tip of the pile, which invalidates the classical plasticity solutions for tip capacity. It supports the usual assumption of adhesion failure occurring at the pile-soil interface. The accuracy of the method was demonstrated by comparing theoretical results with field measurements on five large-diameter test piles [2]. [3] A numerical analysis was conducted to predict the termination criteria of bored piles under axial loading. The study investigated the influence of overlay sand thickness and properties, as well as the characteristics of the founding rock strata. The analysis was performed using PLAXIS 3D Foundation 1.1 software, with axial loads on the pile calculated according to IS 14593:1998. Socket length was predicted for different overlay sand thicknesses and densities, as well as various rock types, based on load-settlement curves. The impact of pile diameter and interfacial shear strength on rock socket length was also studied. The predicted rock socket length was found to be comparable with IS 14593:1998 recommendations.

[4] Presented a new method for settlement analysis of axially loaded piles in multilayered soil, and applies it to two case studies where load tests were conducted on nondisplacement piles. The method involves solving differential equations that govern the displacements of the pile-soil system using variational principles.

The required input parameters for the analysis were the pile geometry and elastic constants of the soil and pile. A user-friendly spreadsheet program called ALPAXL was developed to facilitate the analysis process. A new empirical method was proposed for simulating the nonlinear point resistance response of single piles in cohesionless soils. The pile-soil system was modeled using a one-dimensional finite element technique. The shear resistance response along the pile shaft was obtained using the t-z curve. While the new method was used to define the tip resistance response, or the p-z curve. A generalized Ramberg-Osgood model was employed to simulate the nonlinear t-z and p-z curves. To validate the method, four examples of field and laboratory tests on piles in sands were considered. The comparisons between the finite element predictions and the laboratory and field observations showed good correlation. The results were relevant to a specific class of problems that involve long piles, submerged or dry sand, and a constant value of the lateral earth pressure coefficient [5]. [6] Proposed analytical method to predict the load-settlement curve for axially loaded piles in clay based on the correlation between the ratio of load transfer to soil shear strength and pile movement. The correlation was established using data from field tests of instrumented piles and laboratory tests of small piles in clay. The resulting correlation was presented in the form of a family of curves that show the ratios of load transfer to soil shear strength versus pile movement as a function of depth. The validity of the correlation curves was verified by comparing computed and actual load-settlement curves for typical field tests. The method proved to be effective for determining the load-carrying capacity of axially loaded piles in clay.

[7] Presented a set of parametric solutions for piles in a Gibson soil, where the modulus increased linearly with depth. The analysis was applicable to piles in layered soil, except for cases where the soil under the pile was more compressible than the overlying strata. An approximate method was also described to calculate pile settlement in nonhomogeneous soils using available solutions for uniform soils. The study briefly examined methods for determining soil modulus values and compared measured and theoretical pile behavior to illustrate the practical implications of assuming a nonhomogeneous soil profile. [8] Examined the behavior of pile groups in soils with non-uniform shear modulus, which varied according to a power law function of depth. The problem was tackled by analyzing the response of a 'receiver' pile, which carried no load at its head, to the displacement field of a loaded 'source' pile. An approximate expression was derived for the receiver pile's response using a model error correction factor, which was deemed useful for practical design purposes. The study also evaluated the proposed model's ability to predict experimental results, and provided dimensionless design charts and an example to illustrate the method. Soft soils often require special consideration in foundation design. Traditional foundation types, such as shallow spread footings, may not be suitable as they can experience excessive settlement or fail to provide adequate support [9].

[10] Investigated the time-dependent behavior of a single pile embedded in a multilayered poroelastic soil under axial loading. The pile was modeled as a one-dimensional bar and discretized using the finite element method. The analytical layer-element method was employed to obtain the fundamental solution for the soil subjected to a unit load. The interaction problem between the pile and soil was solved by deriving the solution in the Laplace transform domain based on the compatibility condition between them, and then taking the inversion of the Laplace transform to obtain the actual solution. The numerical solutions obtained were consistent with existing ones, indicating the accuracy of the proposed theory. Examples were provided to demonstrate the effects of the stiffness ratio, length-radius ratio, stratification of the medium, and time factor on the interaction problem.

II. METHODS AND MATERIALS

The software PLAXIS 2D is used for the present numerical analysis. PLAXIS 2D is a finite element software package used for geotechnical analysis of soil and rock structures. It is widely used for the analysis of foundations, embankments, tunnels, excavations, and retaining walls. PLAXIS 2D can simulate complex soil-structure interaction problems and can model a wide range of soil types and material behavior, including nonlinear soil behavior, soil plasticity, and soil consolidation. The software also allows for the analysis of both static and dynamic loads.

The analysis begins by modeling different types of soils as elastic-perfectly plastic material based on the Mohr-Coulomb model, with drained behavior. The pile, on the other hand, is modeled as a linear elastic material with non-porous behavior. To model the deformation and stresses in soils, 15 node wedge elements are used, and exact values of displacement, stress, and strain are extracted from the output tables. To restrict run time, the mesh is generated with medium elements. In this analysis, the interface between the pile and surrounding soil is considered, and an axisymmetric model is used. Thus, only half of the model is considered. The behavior of load settlement and base pressure is determined by considering a single conventional pile with a diameter of 1m and a length of 20m embedded in soil layers. For the mesh dimensions, a lateral boundary distance of 20m from the axis of symmetry and a lower border position 10m below the pile's base are selected.

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To model a stepped pile, a conventional stepped pile is considered, with the diameter of the upper portion being less than that of the lower portion. In contrast, an inverted stepped pile has a larger diameter in the upper portion than in the lower portion. To analyze these stepped piles, the diameter of the upper portion is decreased by 0.1D to 0.3D, and the corresponding diameters for the lower portion are determined by keeping the same volume and length of the pile as the conventional single pile. Similarly, for the inverted stepped pile, the diameter of the lower portion is decreased by 0.1D to 0.3D, and the upper diameters are calculated accordingly. The vertical model boundaries are fixed in the x-direction and free in the y-direction, while the bottom model boundary is fixed in all directions, and the top boundary is free in all directions. By modeling the soil and pile with these specifications, the behavior of load settlement and base pressure can be accurately determined. The properties of soil and pile are illustrated in Table 1.

Table 1. Properties of soil and pile

Parameter	Clayey sand (Brown)	Silty sand	Clayey sand (Red)	Deep sand	Pile	Unit
Unit weight (γ)	16.7	18.8	19.8	17.6	24	kN/m^3
Young's modulus (E)	9150	13510	13570	19300	$29.2e^6$	kN/m^2
Poisson's ratio (ν)	0.3	0.3	0.3	0.3	0.15	--
Cohesion (c)	13	12	14	17	--	kN/m^2
Friction angle (Φ)	26	23	23	23	--	^{0}
Angle of dilatancy (ψ)	0	0	0	--	--	^{0}

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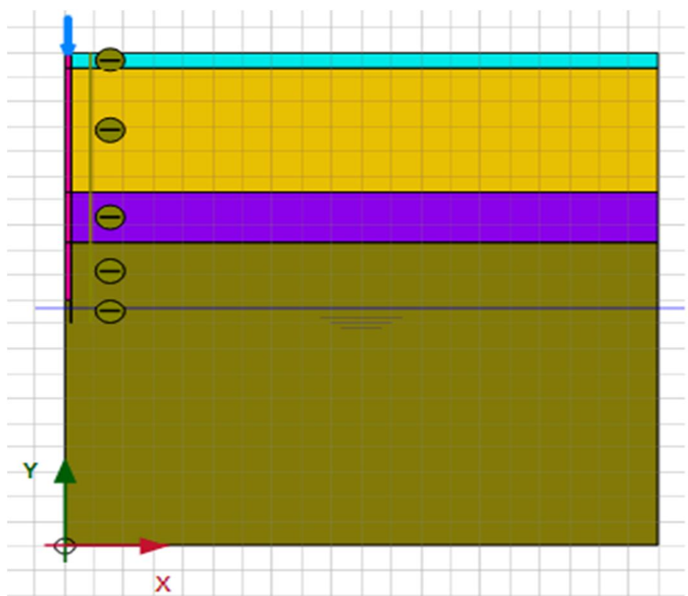

Fig. 1. Schematic diagram of problem

III. RESULT AND DISCUSSION

The results of the present study are in good agreement with those of Neves et al. (2001) and validate their findings as mentioned in Fig. 2. For the validation purpose the same properties of soil and pile are used as mentioned in Table 1. The diameter of single conventional pile is considered as 0.4m and length of pile as 10m. The water level is considered at 10.4m below the ground surface.

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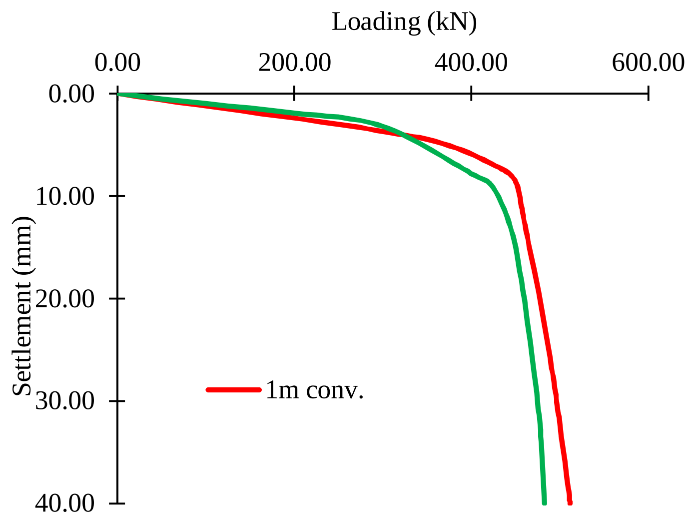

Fig. 2. Load settlement curve for 0.4m dia. and 20m length of conventional pile

A. *Load Settlement Response*

In present study, the load settlement response of pile for dia. 1m and length 20m is studied. For the same the material properties for pile and soil are used as mentioned in Table 1. The applied load is 4000kN on the top of the pile and corresponding settlement is obtained by FEM method as shown in Fig.

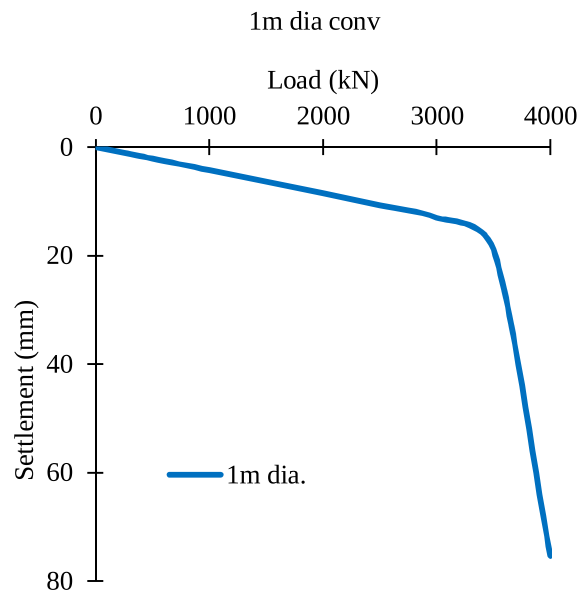

Fig. 3 Load settlement response for 1m dia. conventional pile.

B. *Axial Force Distribution Of The Pile*

Axial force distribution of the pile is studied for the conventional and stepped pile. In case of conventional pile the dia. of pile is used 1m and its length is considered as 20m. In stepped pile the dia. of upper step has been reduced by 0.1D to 0.3D that means the dia. used for upper portion of step is 0.9, 0.8 and 0.7m and correspondingly lower step dia. is provided. For the same total length and volume of the pile kept constant as like single conventional pile.

Fig. 4. depicts that the axial force distribution of the pile when different quantity of loading is applied over the pile. The applied force quantity varies from1000 to 4000kN and its axial force distribution of the pile with respect to the depth has been carried out. Here, similar kind of trend has been observed even loading quantity is varied.

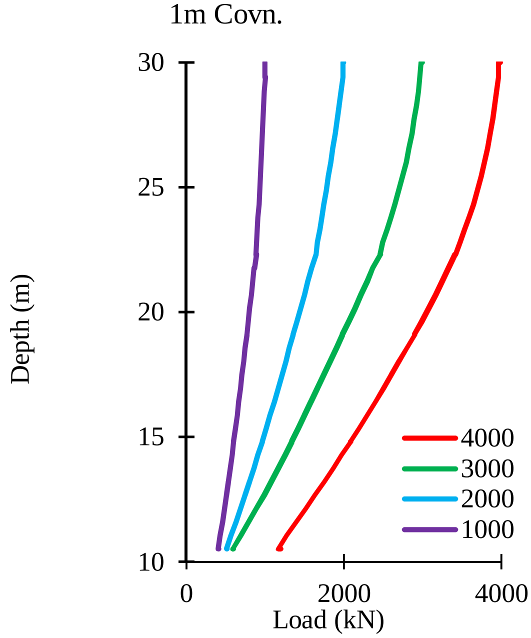

Fig. 4 Load distribution curve for single conventional pile of dia. 1m

Under vertical loading, the stepped pile exhibits a sudden drop in the axial force distribution curve where there is a change in diameter between steps, indicating significant attenuation. This attenuation increases as the applied vertical load increases. Figure 5 illustrates the axial force distribution with respect to the depth of a single stepped pile, where the step length is half the total length of the pile. The upper step of the pile has a diameter of 0.9m, while the lower step has a diameter of 1.09m. These findings suggest that the design and construction of stepped piles should take into account the impact of diameter changes on axial force distribution.

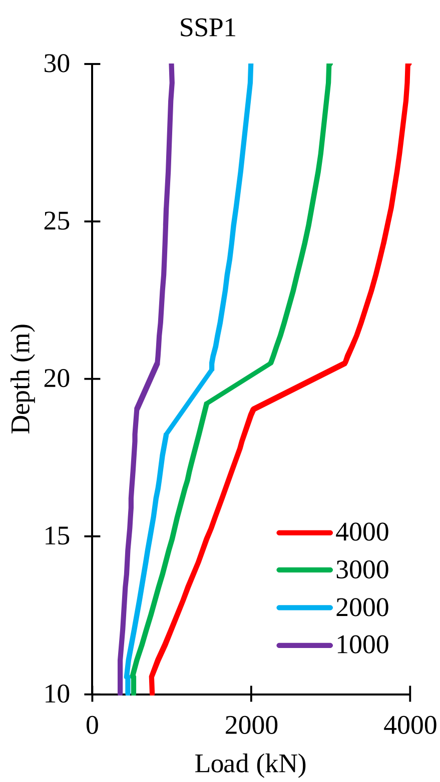

Fig. 5 Load distribution curve for single stepped pile of upper step dia. 0.9m

Figure 6 depicts the axial force distribution of a single stepped pile with a step length half of the total pile length. The upper step has a diameter of 0.8m, while the lower step has a diameter of 1.16m. In Figure 7, the axial force distribution of a single stepped pile is shown where the step length is half of the total pile length, and the upper step has a diameter of 0.7m, while the lower step has a diameter of 1.23m. The load transformation to the soil beneath the pile is less in the case of stepped pile, as compared to the conventional pile. This is due to the increased load-bearing capacity of the skin friction effect in the sandy soil. Moreover, the load settlement response of the stepped pile increases when a larger diameter is provided at the lower step, as opposed to the upper step. These findings contribute to our understanding of the axial force distribution of stepped piles and can inform the design and construction of such piles in various applications.

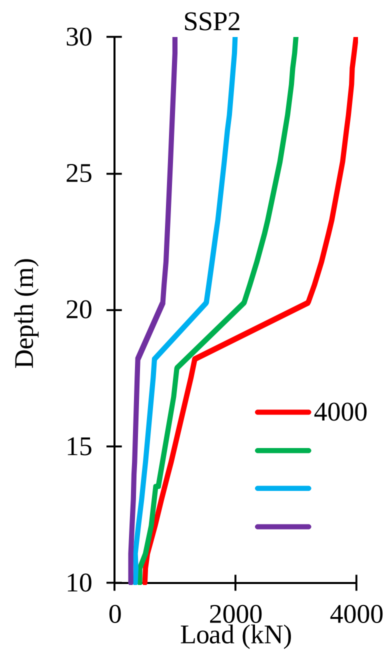

Fig. 6 Load distribution curve for single stepped pile of upper step dia. 0.8m

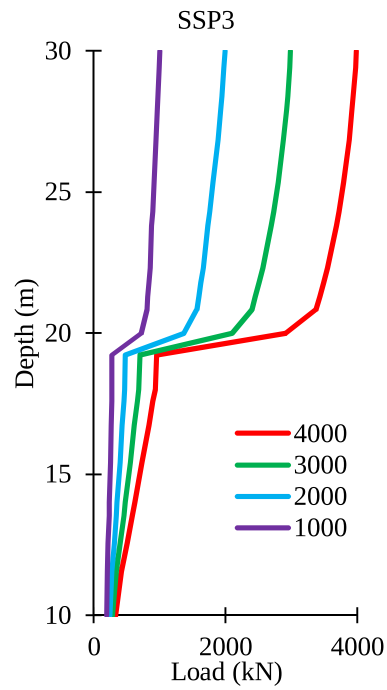

Fig. 7 Load distribution curve for single stepped pile of upper step dia. 0.7m

IV. CONCLUSION

Numerical study of the vertical bearing capacity of stepped pile under axial load was conducted and the results are presented herein.

1) The load carrying capacity of stepped pile is more as compare to the conventional pile.
2) Load transformation curve abruptly changes where there is a change in diameter between steps.
3) Intensity of load transformation to the beneath of pile in case of stepped pile is less because the larger dia. of step increases the skin friction and more load is carried by skin friction.

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