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Analysis of Load Transformation Behavior of Stepped Rigid Pile

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Abstract:- In the present study, an analysis was conducted to assess the load-bearing capacity, shear stress distribution along the pile and soil interface, and load transmission to the depth for both conventional rigid piles and stepped rigid piles. The conventional pile had a diameter of 1m and a length of 20m. For the stepped rigid pile, the upper portion was reduced by 0.1D and 0.2D of the pile diameter, while the diameter of the lower portion was adjusted to maintain the total length and volume of the stepped rigid pile, similar to the conventional pile. The results indicate that the stepped rigid piles demonstrate superior load-bearing capacities compared to the conventional piles.

Keywords:- *Stepped pile; shear stresses; load transformation. FEM.*

I. INTRODUCTION

Pile foundations are utilized when the topsoil lacks the ability to support loads of a structural foundation, either due to low bearing capacity or the potential for excessive settlement. The primary function of a pile is to transfer the weight of the foundation to deeper soil strata that possess greater strength and load-bearing capacity and are less compressible. However, due to their higher cost compared to shallow foundations, pile foundations should only be chosen when shallow foundations are unable to meet an acceptable factor of safety against bearing failure in the foundation soil or acceptable settlement over the structure's lifespan. Several factors may contribute to these design criteria, such as the nature and magnitude of structural loads, settlement-sensitive structures, and soil type. Thus, the objective of pile foundations is to fulfill the design criteria by transferring the structural loads to the deeper, stable, and stronger soil strata. In some cases, the situation may be more complicated when stronger soil layers of relatively small thickness exist above weak soil that extends to great depths. In this scenario, using pile foundations entails some uncertainties, and the behavior of piles cannot be predicted with certainty. The uncertainties in pile behavior arise from soil non-homogeneity and the alteration of soil properties following pile installation. Furthermore, most of the rules or approaches for estimating pile-bearing capacity and deformation take into account the general scenario of weak soil overlaying strong soil. Since pile behavior primarily depends on soil properties and the method of pile installation, considerable efforts must be undertaken to determine soil properties through laboratory and field tests.

Researchers have extensively studied settlement analysis of axially loaded single circular piles using various methods and approaches in both homogeneous and non-homogeneous soils. Available settlement analyses either assume soil resistance can be represented by a series of disjointed springs or that it is a continuum. Traditional continuum approaches require expensive numerical techniques to obtain solutions, but efforts have been made to solve this problem with mathematical rigor.

[1] analyzed the settlement behavior of a single granular pile at varying depths under axial loading, quantifying the effects of parameters on settlement reduction for rational design. They presented results of end-bearing and floating granular piles constructed in soft soil. [2] presented a new empirical method to simulate the non-linear point resistance and shear resistance response of single piles in cohesionless soil using the concept of t-z curve. [3] utilized an elastic continuum approach to study the response of non-homogeneous floating granular piles in homogeneous soil. [4] analyzed the bearing capacity and load deformation of single piles under vertical loads in granular soil, studying the mechanism of shaft friction and the effect of deformation modulus on bearing capacity using the FLAC program.

[5] presented the behavior of a perfectly plastic elastic model (Mohar Coulomb) and an elastoplastic model with strain hardening (Nova 1982) in terms of load settlement and force distribution along pile surface and compare numerical results with experimental ones. Rigorous analysis based on Mindlin's solution for a point load in an ideal elastic medium was used by [6] to obtain the response of rigid and compressible single piles embedded in a homogeneous isotropic linear elastic soil medium. One common assumption made in settlement analysis, as discussed [7], is that the soil resistance can be modeled as a series of disconnected springs.

This study analyzes the load transformation behavior and stress distribution along the pile and soil interface of a stepped rigid pile. In this study, the total length and volume of the pile were kept constant in all cases like conventional piles.

II. METHODS AND MATERIALS

The study analyzed conventional and stepped rigid circular piles with a length and diameter of 20m and 1m, respectively. The 100mm prescribed settlement was applied on top of the pile in multilayered granular soil. The water level was set at 10.4m from the top surface of the soil. The horizontal boundary is considered at 20m from the axis of the center of the pile and its depth is 30m.

The current study assumes that there is no slip or yields at the interface of pile and soil, the soil medium is isotropic and non-homogeneous, and an axisymmetric configuration has been adopted, with the axis of symmetry aligned with the axis of the pile. The pile sides are considered perfectly rough and rigid, and the analysis is carried out under no-tension conditions in the soil.

Table 1: Properties of soil and pile (Neves et al. 2001)

Para-meter	Clayey sand	Silty sand	Clayey sand	Deep sand	Pile	Unit
γ_t	16.7	18.8	19.8	20	--	kN/m3
E	9150	13510	13570	19300	29.2x10^6	kN/m2
ν	0.3	0.3	0.3	0.3	0.15	--
C	13	12	14	17	--	kN/m2
Φ	26	23	23	23	--	^{0}

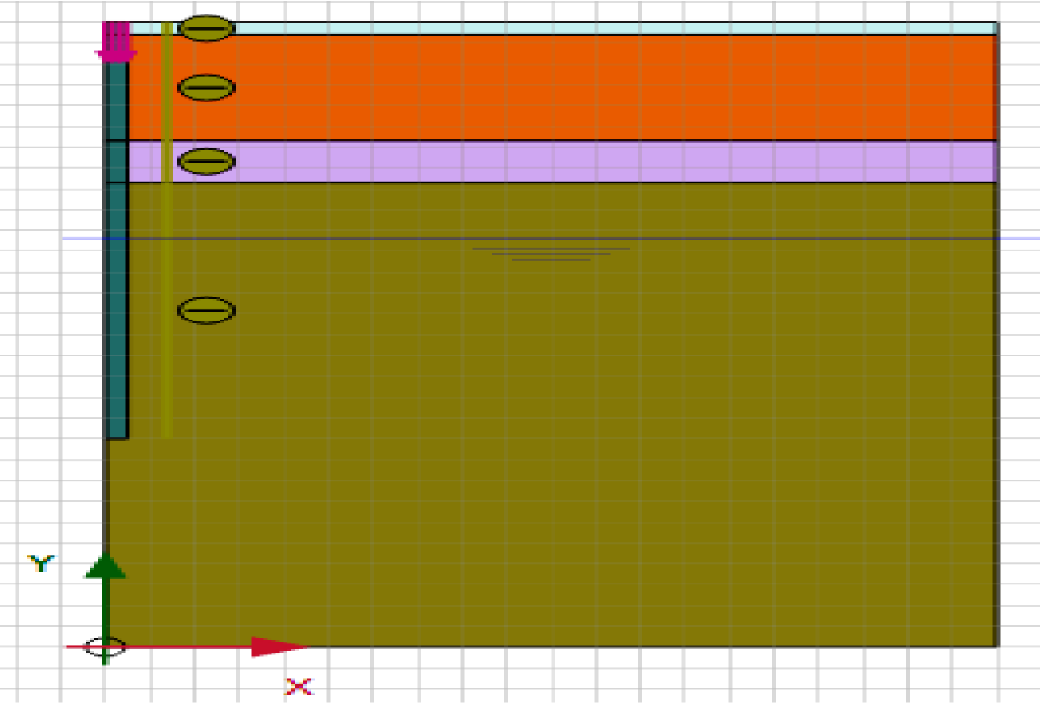

Fig. 1: The FEM model

Soil properties were utilized to analyze the load settlement for all cases mentioned in Table No.1. The first layer had a thickness of 0.00m to 0.6m, the second layer 0.6m to 5.7m, the third layer 5.7m to 7.7m, and the fourth layer 7.7m to 30m. The analysis included the application of Mohr-Coulomb and drained condition to each layer of soil and a linear elastic and non-porous condition for the pile.

In this study, a numerical model was developed in PLAXIS 2D and analyzed using the Mohr-Coulomb failure criterion due to its simplicity. An axisymmetric condition was considered with 15 nodded triangular elements and a medium finite element distribution mesh. The sandy soil was considered drained, and a non-porous linear elastic condition was assumed for the rigid pile. The initial stresses in the sandy soil were generated according to the ko procedure (jacks formula). Here, a single step is incorporated and the diameter of the upper portion of the step is varied by 0.1 D to 0.2D i.e. it is kept as 0.9m and 0.8m respectively.

III. RESULT AND DISCUSSION

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.

Table 2: The different ratios of dia. of steps of 1m rigid pile

S. No.	Name	Upper step Dia. (m)	Lower step Dia. (m)
1	RP	1	1
2	SRP1	0.9	1.09
3	SRP2	0.8	1.16

A. *Effect of step on LBC of Rigid Pile:*

This section focuses on the analysis of a rigid pile with a diameter of 1m and a length of 20m. The model is subjected to boundary conditions with a radius of 20m and a depth of 30m. A single step is introduced by varying the stepped length to L/2. Corresponding loading-bearing capacities are obtained for a prescribed settlement of 100mm. The total length and volume of the stepped pile remain the same as the rigid pile. The upper portion of the stepped rigid pile (UPSRP) is reduced by 0.1D and 0.2D, and accordingly, the diameter of the lower portion of the stepped rigid pile (LPSRP) is increased to maintain the total volume like the rigid pile.

Fig. 3 shows that the loading bearing capacities for 100mm prescribed settlement are 655.78, 699.89, and 746.64kN/rad for RP, SRP1, and SRP2, respectively. The results indicate an improvement in LBCs of 6.72% and 13.85% SRP1 and SRP2, respectively, compared to the rigid pile. The same properties are used for this analysis as in the Neves et al. 2001 study.

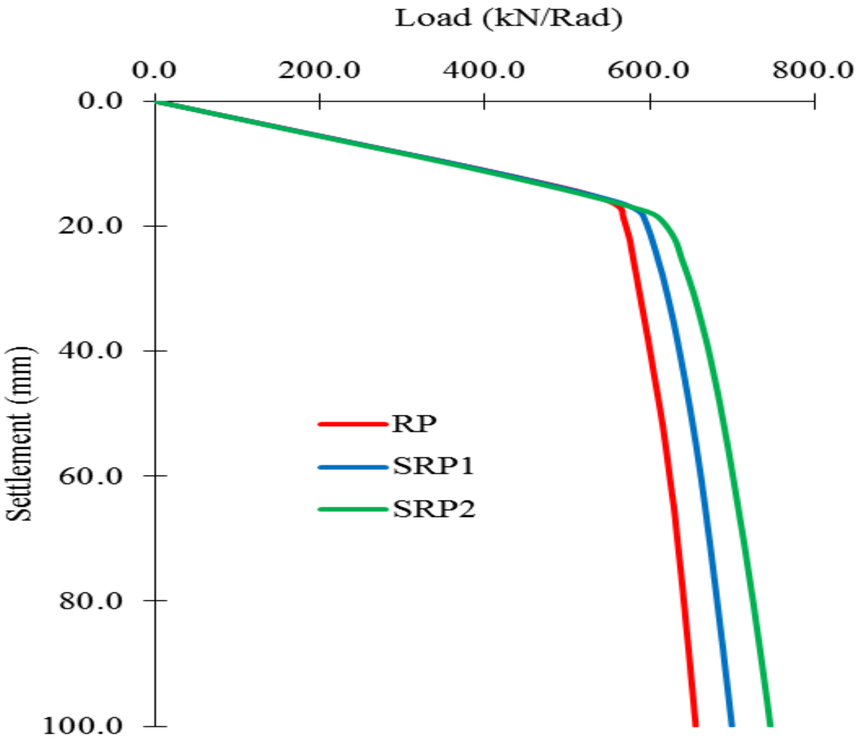

Fig. 2: Load settlement response of stepped rigid pile

B. *Effect of step on load transformation of Rigid Pile:*

The load-carrying capacity of stepped rigid piles exceeds that of conventional piles due to the greater diameter of the lower portion. The load transformation for conventional piles is a smooth curve, while for stepped rigid piles, it increases rapidly in the upper portion up to the first half of the step and then changes abruptly at the change in diameter in the lower portion. The load transformation in the lower portion is less in stepped rigid piles compared to conventional piles. Fig. 3 illustrates load transformation for a conventional rigid pile with a diameter of 1m and a stepped rigid pile with upper diameters of 0.9m and 0.8m and lower diameters of 1.09m and 1.16m, respectively. SRP2 performs better than SRP1 because the diameter of the lower portion is greater. It can be concluded that the load-bearing capacity of stepped rigid piles can be improved by increasing the diameter of the lower portion up to a certain limit.

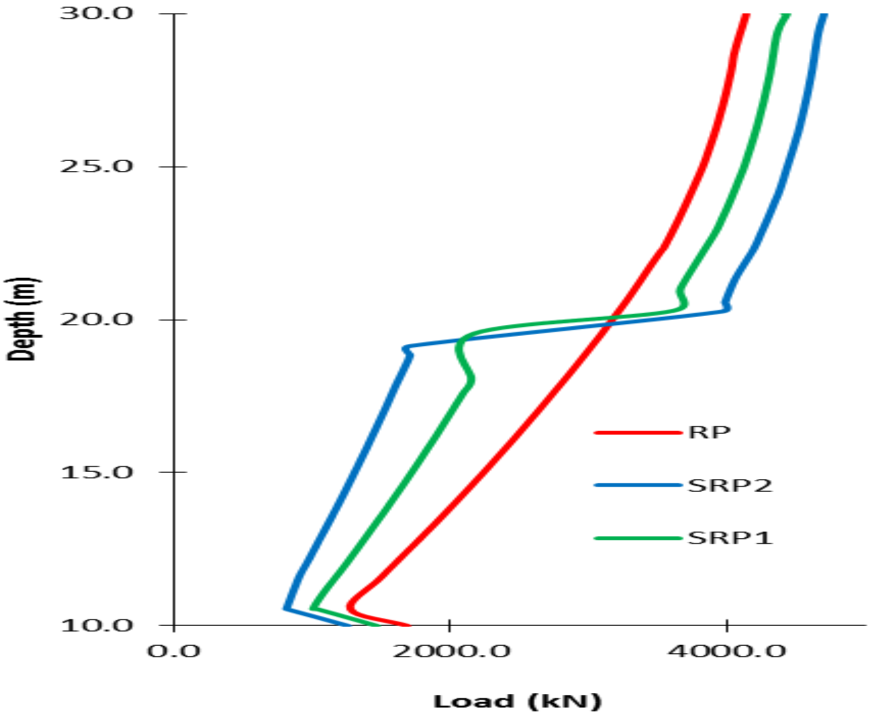

Fig. 3: Load transformation of stepped rigid pile

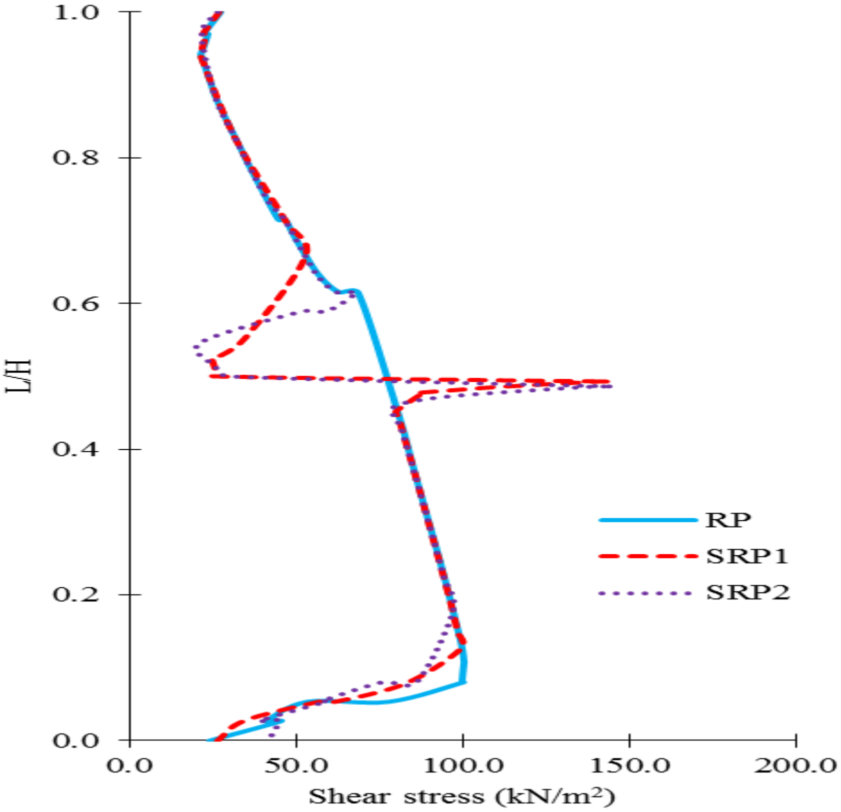

Fig. 4: Shear stress distribution for stepped rigid pile

Fig. 4 illustrates the shear distribution variation along the normalized depth of a rigid pile and a stepped rigid pile. The depth of the pile is normalized based on the height of different points. For the conventional rigid pile, the shear stress distribution at the upper part is lower, gradually increasing with the depth of the pile. However, in the case of the stepped rigid pile, the shear stress at the upper portion of the step is somewhat similar to that of the conventional rigid pile. However, there is an abrupt change in shear stress with the change in the diameter of the step. Furthermore, at the lower side of the stepped pile, the shear stress behaves similarly to the conventional rigid pile.

IV. CONCLUSIONS

In the present study, a numerical investigation was carried out to analyze the vertical bearing capacity, Shear stress distribution along the soil–pile interface, and load transformation of a stepped pile under axial load. The findings of this study are presented below.

- The stepped pile exhibits a higher load-carrying capacity in comparison to the conventional pile.
- The shear stress distribution curve undergoes an abrupt change at locations where there is a variation in diameter between the steps.
- In the case of the stepped pile, the load transfer to the underlying layers is reduced due to the larger diameter of the step. This increase in diameter enhances the skin friction, resulting in a greater portion of the load being carried by the skin friction mechanism.

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