Numerical analysis of the performance of pile cap on a single pile for a lateral bearing capacity in layered soil

Alex Atanaw Alebachew¹ and Prof. Denzel M W Gui¹

¹Department of Civil engineering, National Taipei University of Technology, Taiwan, Taipei

E-mail: alex.atanaw@gmail.com

Abstract. Deep underground infrastructure is booming technology in developing countries, and these construction techniques are mostly used in developed countries at present. Pile foundation among many types of deep structures, it is significantly researched and built to sustain and transfer loads from superstructures to deep soil, in either case, the load from the superstructure is very high or the soil at shallow depth is too weak. Piles are subjected to axial, horizontal, momentary, and combined loading systems as a single pile or pile group system connected to the reinforced pile cap on top of the pile to share or transfer loads through the wall and tip to the surrounding soil. Along with elastic solid pile-pile cap characteristics of materials, a limited number of numerical and analytical studies are published even merely on a homogeneous soil placement of the pile cap model. However, The soil’s natural deposit at a significant site may not always be found homogeneous on which pile-caps and piles are placed. To fill the gap of an intricated multi-physics soil-structure interaction problems, successive analysis is incurred to be proliferated. The study presented a numerical analysis of the influence of the pile cap on the single laterally loaded pile, while the embedding of the pile cap varied on the layered soil profile. The standard linear static numerical analysis software ABAQUS was used to model 3D pile cap-pile and layered soil with subjected lateral load and relevant boundary conditions. The result of the analysis was plotted varying the embedding of the pile cap on clay overlaid sand and sand overlaid clay interchangeably taking into consideration other influencing parameters (pile capsize and vertical load). The increase in pile cap embedment on clay overlaid sand slightly increases the lateral resistance of the pile cap for the first few increments and small non-linear variation for further embedding from the analysis has resulted. However, the performance of the pile cap for lateral load resistance was significantly increased as the depth of embedding of the pile cap is increased on sand overlaid clay. Besides, the size of the pile cap has a direct proportion for lateral resistance, and the vertical load exerted on a pile cap has not had a significant influence. The study comprehensively emphasized the interaction of piles with simple soil physics problems, but multi-soil physics problems with pile interaction should be analyzed for future study.

Keywords:- Lateral capacity, pile cap, single pile, layered soil, numerical simulation

1. Introduction

In structural engineering, the construction of deep underground structures is booming technology. Pile foundation between many types of deep structures, it is significantly researched and built to sustain and transfer loads from superstructures to deep soil, in either case, the load from the superstructure is very high or the soil at shallow depth is too weak. The analysis of the pile foundation is a sensitive program, while inconsistencies in the natural soil or soil can lead to major structural failure and consequently to high design costs. Researchers in the past and present dealt a complicated investigation of piles subjected to vertical loads, laterally or combined loaded piles are widely practiced as single and grouped systems.
Broms(1964) and Hansen(1961) used basic analytical formulae to evaluate the laterally loaded piles' deflection, rotation, moment, and bearing power. Winkler ‘s technique, p-y curve, elastic theory, finite element methods, and, in some cases, centrifuge modeling are also involved in solving theoretical problems of the pile and pile cap structures that are subject to horizontal loading. Researchers on the aforementioned methods performed several studies to alleviate the introduction of parametric effects on the activity of the pile-pile cap as single and/or grouped structures. Palash (2018) used a strut and tie model to design a pile cap capacity. Most importantly the spacing of the piles on a group influenced the cap's resistance capacity. Experimental small-scale analysis of the pile cap thickness effect on the pile group was investigated Balamba Sjachrul(2017). The cap thickness varied from 2D to 5D. D is the diameter of the pile. The study indicated that the thicker the pile cap, the smaller the pile deflection. 3D finite element geotechnical software has been used to analyze the impact of pile cap thickness on lateral pile head movement relative to pile spacing Tjie-Liong( 2015) the center-to-center pile spacing played a significant role in the effect of lateral pile head movement than the pile thickness did. Hazarika(2013) and Tahghighi(2011) presented a review of different parametric effects of the impact of the pile cap on pile groups subject to horizontal loads.

Full experimental analysis of single pile and pile group interaction with pile cap at a different position from the surface of the ground and various combinations of loads imposed on the cap was presented M. Sugunadevi(2018). The analytical result reveals the contribution of the cap is significant on a sand placed cap. In a simple soil-pile model of this study, the resistance of the cap increases considerably with an increase in surface embedding. A numerical simulation model using ABAQUS software has been presented on homogenous clay soils subjected to a single pile of vertical and horizontal loads Cuihong Ding(2010). In a considerable increment of the pile cap area, the pile contribution for lateral resistance became high and the embedment depth of the cap has also affected the lateral resistance in a different way of the other studies. Three-dimensional Lagrangian analysis Shen-Kun(2016) deployed p-y curve pile cap influence on piles subjected by lateral loads has been drawn in a parametric variation of pile capsize and pile length on clay soil. It was discussed that the pile cap size affected the first quarter of the pile for lateral resistance in capsize increment. Ahn (2005) Describe the finite element cam clay soil model analysis of single and pile groups. The paper demonstrated the effect of pile cap lateral resistance capacity at a variable geometry of pile cap size for short and long pile model. The pile diameter was also concerned with the effect of the resistance of the pile cap Hijran Aboud Aljanabi(2020). Laboratory analysis of laterally loaded piles on clay soil was discussed. The amount of moisture and the degree of saturation directly impact the lateral resistance of the piles.

Studies analyzed pile on a homogeneous soil layer in different methods showed an inadequate considerable effect of pile cap on single piles for lateral resistance ability. The natural characteristics of soil below the ground surface and its contact with the pile can not enable researchers to comprehend their findings to a common level. No numerical analysis of the pile cap effect on homogeneous sand was performed and the pile cap impact on a homogeneous clay layer was different from the pattern observed on a homogeneous sand layer analytically analyzed.

The knowledge gap on the foundation of the pile can be understood while consecutive research is to be carried out. This research, therefore, emphasized the finite element approach of evaluating the effect of the pile cap on the single pile at specific embedding of the pile cap, interchangeably on clay overlaid sand and overlaid clay. In the research pile, cap sizes were taken into account. Besides, the numerical model on this study met separately and in combination with vertical and/or lateral load.

2. Method and materials

A finite element method of numerical analysis was carried out using simple soil and pile-pile cap-system material models. ABAQUS standard linear static numerical analysis program was used to model 3D pile cap-pile and layered soil with subjected lateral load and related boundary conditions. In the research, the layer of the soil model has taken into account sand and clay interfacing elements on which the pile cap and the pile combination is placed in. the natural deposit of the study area constitutes clay covered sand soil, however, sand-covered clay layered soil was assumed to keep their mechanical properties the same as the natural existence. This establishment has been assumed to evaluate the conditional variance of the lateral capacity of the pile cap while it is placed in the likely soil profile system. Relevant soil constitutive test data have been collected from projects found under construction, particularly samples are collected on the Megech Dam in Ethiopia's intake tower and conduit areas. The Mohr coulomb elastoplastic layered soil model and a single elastic solid pile model were used due to the limitation of available test results.
Interaction of the laterally loaded soil pile cap should be modeled on 3D element geometry to stabilize the rigid body movement. The model constitutes typical elements of non-homogeneous soil with a size of 10 x 5 x10 m a plane of symmetry about the x-axis and the topsoil layer in both cases was modeled up to 1.2m depth. A non-displacement concrete pile –pile cap interaction elements were analyzed. the pile size was assumed to be 0.3 m in diameter and 9 m in length, and the pile cap size varied arbitrarily from 0.6 m to 1.6 m, with a constant thickness of 0.6 m, the extrusions of the pile zone in a two-layered soil model incapable to mesh the 3D element with quadratic brick element.

The quality of the mesh and the convergence problem of the analysis was verified using C3D10 quadratic tetrahedron elements for both the soil element and the structural components to allow a smooth transition of the degree of freedom of the rigid body. The general surface-to-surface contact between the pile and the pile cap and the soil wall-to-pile Tie contact with an interaction angle of 0.75 $\phi$ was assumed for clay and sand with their corresponding internal friction angle value.

| Material type | $\rho$(kg/m$^3$) | $c'(kPa)$ | $E_s/E_c$(Mpa) | $\phi$(0) | $\mu$ |
|---------------|-----------------|-----------|----------------|----------|-------|
| Clay soil     | 1650            | 25        | 3              | 10.2     | 0.32  |
| Sand soil     | 1700            | 1         | 7              | 31.4     | 0.27  |
| Concrete      | 2500            | -         | 3000           | -        | 0.160 |
3. Analysis result

The results were discussed taking into account the following parameters: Pile cap position as shown below Fig. 1. The analysis focuses significantly on layered soil by interchangeably varying the overlay and underlay forms of material. The plot taken into account in the present study was the effect of the pile cap on piles at a different parametric value of the pile cap geometry and additional vertical load impact.

3.1 Pile cap embedment from the surface

In two cases of soil modification, the study was performed i.e. clay overlaid sand and sand overlaid clay was interchangeably specified to the numerical simulation. The parametric study of lateral pile cap resistance capacity was studied at different layered soil pile cap locations: at the surface, 0.3 m, 0.5 m, 1 m, 1.2 m, and 1.5 m below the ground surface of both soil configurations. In this case, the pile capsizes was constant throughout the embedment of the pile cap.

![Figure 1. a) load-displacement graph of pile cap on clay covered sand soil](image-url)
For both cases, the underlaid soil extended to 1.2 m from the surface to exploit the soil layering effect. As shown in the first graph (fig1.a) the lateral resistance increases for the first three consecutive increments in the depth of the pile cap. The lateral capacity is not modified from the same graph above at all depths up to the first 10 mm displacement of the cap. At 25 mm displacement for 0, 0.3, and 0.5 m embedding depth the lateral resistance is 89 kpa, 96 kpa, and 105 kpa respectively. The resistance potential for the remaining embedding of the cap with the same displacement of 25 mm was increased insignificantly. The lateral resistance appeared to decrease arbitrarily in a further increase of the displacement for all embedding depth of the cap.

The contribution of the pile cap to lateral resistance in sand-covered clay soil increases significantly as the embedding depth increases. From fig 1.b above the lateral capacity, increase appropriately from 35 kpa to 65 kpa with an increase in embedding depth at a displacement of 10 mm. At an embedding depth of 1.5 m below the surface, the lateral resistance of the cap increased by almost 50% from the surface of the sand-covered clay soil layer. Differently, when the pile cap is placed in the clay region of the soil in sand overlaid clay layered structure, the resistance appears to decrease arbitrarily in a further increase of the displacement for all embedding depth of the cap.

3.2 Influence of capsizing

The present study was carried out with 0.6 x 0.6, 1 x 1, 1.2 x1.2, and 1.6 x 1.6 pile capsize with a constant thickness of 0.6m. Analysis of the capsize effect was performed by modeling the pile cap at ground level from fig 2 below the size of the pile-cap has a direct proportion for its lateral resistance capacity. The increase in the cap's lateral capacity relative to the initial capsize at a 10 mm displacement was 28.3%, 46.7%, and 61.7% respectively. Increasing lateral resistance is non-linear but important with a rise in capsizes.
3.3 Influence of vertical load

In addition to the horizontal load, an axial load was added to the pile cap. The study was conducted with a vertical load applied of 0, 50kN, 80kN, and 120kN respectively. As seen in figure 3 below the pile cap has very few lateral resistance contributions while being subjected to additional vertical loading. Entirely from the curve for vertical loads of 50kN, 80kN, and 120kN have almost a constant lateral resistance.
4. Conclusion

The numerical study of pile-pile cap interaction on layered soil has several influencing parameters for lateral resistance capacity. The findings of the study varied the embedding of the pile cap on clay overlaid sand and sand overlaid clay, considering other determining parameters. The increase in the embedding of the pile cap on clay overlaid sand increases the lateral resistance of the pile cap for the first few increments slightly and underwent a non-linear curve for further embedding from the analysis. The pile cap’s output for lateral load resistance has been significantly improved as the pile cap's embedding depth on sand overlaid clay is improved. Besides, the size of the pile cap is directly proportional to the lateral load, but the vertical load applied on a pile cap did not have a major effect. The research has comprehensively emphasized the interaction of piles with basic soil physics issues, but for future analysis multi-soil, physics problems with pile interaction should still be studied.
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