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Response of Pile foundation to Horizontal Load: A Review

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ABSTRACT

Deep foundation has a significant role in sustainable and safe development of infrastructure. The present study dealt about the behavior of laterally loaded pile foundation. Initially, a review of several recommendations and guidelines made by industry consultants for lateral bearing capacity of pile in clay has been summarized. A typical inconsistency has been found in these hypotheses. The paper further investigated the various factors influencing the behavior of laterally loaded pile foundation. It may be concluded that the interaction of vertical loads reduces bearing capacity of laterally loaded pile. Furthermore, the presence of clay layer in sand deposit effects lateral behavior significantly. Extra deflection may be observed when pile installed in group as compared to single pile due to increase in flexibility.

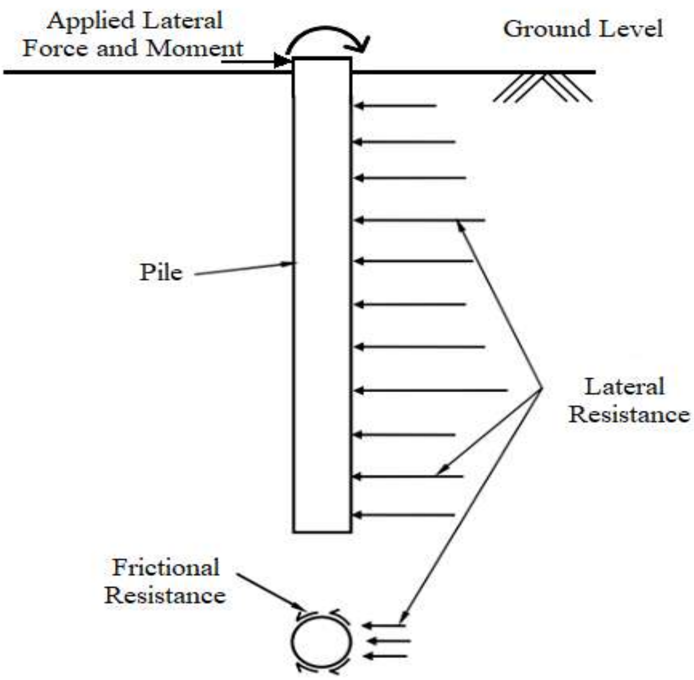
Keywords: Pile foundation, Lateral loading, Layered soil, Bearing capacity, Group effect.

I. INTRODUCTION

Pile foundations have been in practice since long, to transfer the load of superstructures to the deep compatible soil or rock strata. High rise buildings, offshore platforms, bridges, defence structures, dams, metro projects, transmission towers, earth retaining structures, wharfs and jetties were few important structures, where pile foundation were frequently used to support vertical and lateral loads. Nevertheless, in all these structures, piles had to carry not only the axial loads, but also the lateral (horizontal) forces and moments. More precisely, in structures like oil production platforms, earth retaining structures, wharfs and jetties, the primary function of piles is to resist the lateral loads for safety of the structure. For tall buildings and transmission towers, wind action may be regarded as the main source of horizontal loading, while, in case of offshore structures, oil extraction platforms, quays, harbors, wharfs and jetties, wave action has the significant contribution as horizontal force. Further, in design consideration seismic forces may come into picture according to the seismic zonation of particular project.

II.MECHANISM OF LOAD TRANSFER IN LATERALLY LOADED PILES

Laterally loaded piles have load transfer mechanism similar to a transversely loaded beam. They transfer the load to the adjacent soil mass by using the lateral resistance of soil. When a pile is loaded laterally, a part or whole of the pile tries to shift horizontally in the direction of the applied load, producing bending, rotation or translation of the pile (Fleming et al.1992, Salgado 2008). The soil in the front i.e. in direction of applied load has been pushed by the pile, which generates compressive and shear stresses and strains in the soil that offers resistance to the pile movement (Figure-1). Hence, the external horizontal forces have been balanced by the total

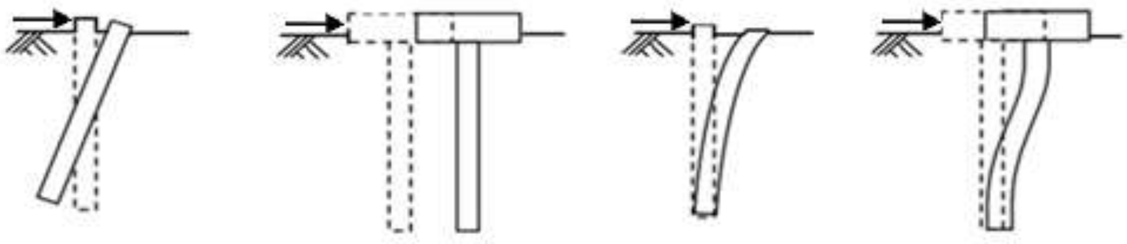


soil resistance acting over the entire pile shaft. Similarly, pile groups designed for horizontal load also have two resistance mechanisms i.e. friction along the sides and base resistance.

Fig.1 Load Transfer Mechanism of Laterally Loaded Piles

III.FAILURE MODES OF LATERALLY LOADED PILES

Pile foundation may fail in different mode, when it has been loaded laterally. Laterally loaded piles may rotate, bend or translate due to transverse nature of load, (Fleming et al. 1992, Salgado 2008). Since the pile moves in the direction of the applied force, a gap may also open up between the back of the pile and the soil over the top few meters. Rigid pile (short and stubby), will not bend greatly would rather rotate or even translate (Figure-2 a, b). However, flexible piles (long and slender) will have a bending behavior because of applied load (Figure-2



c,d).

(a) Rotation (b) Translation (c) Rotation (d) Translation

Fig. 2. Kinematics of Flexible Pile (a, b) and Rigid Pile (c, d)

IV. DESIGN RECOMMENDATION

Various design recommendation had been given by different researchers to calculate the bearing capacity of laterally loaded pile foundation. A few of them may be summarized as follow;

4.1. API Recommendation (1950)

American Petroleum Institute has suggested the formula to calculate the lateral capacity of pile in clay. In the current industry guidelines this formula is widely accepted for offshore pile design, such as the method for calculating the ultimate lateral bearing pressure (P_u) is mainly based on the back analyses of some limited field pile tests performed in the 1950s. The recommendation is:

$$P_u = (3+Jz/D)\, S_u + \gamma\ Z$$

Where:

S_u = the undrained shear strength of the soil at the depth of consideration z,

J = Empirical factor (dimensionless)

D = Diameter of pile

γ' = effective unit weight of the soil

4.2. Jeanjean Recommendation (2009)

On the basis on centrifuge experiments and finite element analyses in lightly over-consolidated clay, Jeanjean suggested then the following expression to calculate the lateral bearing capacity factor Np, defined as Pu/Su, following the framework proposed by

$N_p = 12 - 4\ e\ (-\ \xi Z/D)$

The parameter ξ is calculated

$\xi = 0.25 + 0{:}05\lambda$ when $\lambda < 6$

$= 0.55\ \lambda$ when $\lambda > 6$

Where $\lambda = S_{um}/\mathrm{kD}$ which denotes a normalized soil strength gradient in a linearly increasing strength profile that can be described by:

$$S_u = S_{um} + kz$$

Where Sum is the shear strength at the soil surface, k is the shear strength gradient with depth.

4.3. Nichols et al. Recommendation (2014)

On the basis of a combined literature and finite element study, Nichols et al. anticipated the following equations to calculate the ultimate lateral bearing capacity:

$$P_u = N_{Po}S_u + \gamma' \mathrm{Np}$$

$$N_{Po} = 4 + 2(\frac{z}{D})^{0.6}$$

V.FACTORS INFLUENCING THE BEHAVIOR OF LATERALLY LOADED PILE

Shape, size and material of pile has great influence on the behavior of pile foundation either loaded vertically or laterally. However, the effect of soil type, characteristics of soil layers, amount of vertical load and size of group can never be neglected.

5.1. Soil Layering Effects

In engineering practice, over a long time of sedimentation process, soils usually show important characteristic of stratification. The mechanical behavior of stratified soil is usually different in the horizontal and vertical directions, hence, it may be response as a multi-layered transversely isotropic material. Thus, it is important to investigate the behavior of a single pile simultaneously subjected to horizontal and vertical loads in multi-layered transversely isotropic soils for the application in engineering practice. Yang and Jeremic (2000) had studied the layering effect with development of two model. It had been perceived that in clay-sand-clay model, the increase in lateral pressure in clay near the interface is confined to a narrow zone. However, in the sand-clay-sand model, the decrease in pressures spread well into the sand layer. Hence, layering effects are of more importance in sand-clay-sand model (Yang and Jeremic 2002).

5.2. Influence of Vertical Loads

Only a few experimental studies have been conducted to investigate the behavior of laterally loaded piles due to Interaction of vertical load. The behavior of the piles in sandy soils under lateral loads is not affected by the presence of vertical loads. Indeed, the lateral load capacities are not changed for very loose sand and slightly increased for loose, dense and very dense sands. The presence of vertical loads decreases the lateral load capacity by as much as 20% and the maximum bending moment by as much as 30% of piles in clayey soil depending on the level of vertical load and the value of the lateral deflection (Hazzar et al. 2016).

When the lateral load is equal to the vertical load, interaction of lateral and vertical load is closely negligible (Young et al. 2017). For a pile group, vertical load increases the confining pressure. The effect of vertical loads on the lateral behavior of piles is more vital when a footing is added above the pile-heads and this effect should not be ignored in pile foundation design practice (Hussien et al. 2014).

5.3. Presence of External Reinforcement

Lateral behavior of pile foundation may be enhanced with application of external reinforcement, e.g. geogrid, genets etc., especially for seismic response. During a seismic event, the kinematic interaction may produce additional internal forces in a piled foundation. These internal forces are a result of an interaction between the soil and the structural element, which entails the complex mechanical behavior of the soil in contact with the pile. Embedding the geogrid mesh had improved the lateral performance of the pile foundation system and reduced its dynamic response. Increasing the geogrid stiffness further improved the lateral performance of the pile foundation as discussed by (Taha et al. 2015).

5.4. Effect of Group Action

Shadowing effect plays an important role in pile group. Load for a group of piles is less than a load for a single pile multiplied by the number of piles because of "shadowing" effect (Wakai et al. 1999). Piles installed in groups at close spacing deflect extra than a single pile subjected to the same lateral load per pile because of group effect. The load-deflection response of piles in groups is softer compared to single pile load-deflection curve. The difference becomes less important with the increase in pile spacing due to the decrease of the shadowing effect. For pile groups with fixed head, the front row in the group carries the highest load, middle and back row piles carry smaller loads for a given displacement. The ratio of the maximum pile head movements under free and fixed conditions varied between approximately 1.3 and 2.4 depending on the pile position and spacing. The shadowing effect reduces at a greater rate in dense sand compared to loose sand. (Elhakim et al. 2014). Group effect is significant to axial spacing of 3 times pile diameters (Brown and Shie 1990). Piles in the group starts to behave as a single piles when center to center distance between them is three times of diameter pile. The efficiency of a pile group for a given spacing decreases with the increase in number of piles in the group due to the increased number of overlapping zones of passive and active wedges (Gandhi and Selvam 1997).

VI. CONCLUSION

In geotechnical engineering, piles have been considered as most potential option to be used for the deep foundation, when the soil layer with low bearing capacity and high deformability needs to be "bridged". Although the main objective of a pile is to withstand vertical forces, however, pile foundations also have to be designed for the situation where the dominant loads were horizontal. Offshore structures have to face wave action and seismic loading during its life span, is the one type of horizontal excitation, while another can be sea wave. Various design recommendation has been assessed in the present study. Factors affecting the lateral behavior of the pile foundation has been discussed. It has been observed that interaction of vertical load decreases the lateral capacity of pile. Due to shadowing effect, more deflection has been observed for pile group as compared to single pile. Deflection of pile has been reported to decrese with inclusion of external reinforcement like geogrids and geonets. Moreover, presence of clay layer in sand deposits have significant effect on lateral behavior of the pile foundation.

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