Interaction between vertical and lateral loads on the response of piles in soft clays

L'interaction entre les chargements verticaux et latéraux sur la réponse de tas dans les argiles Douces

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ABSTRACT
The paper presents the results of three-dime2nsional finite element analysis of a single pile installed in homogeneous soft clay under individual lateral load and combined vertical and lateral loading. The interaction between vertical and lateral loads on piles has been analyzed using the finite element program GEOFEM-3D. In this analysis, the pile is treated as linear elastic and the behaviour of soil has been idealized using non-associated elastic perfectly plastic based Drucker-Prager constitutive model. The numerical results presented in this paper highlight the effect of vertical load interaction on the lateral load deflection response of pile with reference to some of the important parameters viz. method of loading, pile head fixity conditions and L/B ratio.

RÉSUMÉ
Le papier présente les résultats d'analyse d'élément finie à trois dimensions d'un tas seul installé dans l'argile douce homogène sous le chargement latéral individuel et le chargement combiné, vertical et latéral. L'interaction entre les chargements verticaux et latéraux sur les tas a été analysée l'utilisation du programme d'élément fini GEOFEM-3D. Dans cette analyse, le tas est traité comme linéaire élastique et le comportement de sol a été idéalisé non-associé d'utilisation le Drucker-Prager basé, parfaitement en plastique et élastique modèle constituant. Le pré-sented numérique de résultats dans ce papier souligne l'effet d'interaction de chargement verticale sur la réponse de déflexion de chargement latérale de tas avec la référence à certains des paramètres importants à savoir. la méthode de chargement, entasser les conditions de fixité de tête et la proportion de L/B.

1 INTRODUCTION

Pile foundations are the preferred alternatives for supporting offshore structures constructed in soft marine clays. These structures are subjected to large wave induced lateral loads and vertical loads due to the weight of the structure and the loads on the platform. Besides, due to high compressibility and low shear strength nature of the soft clays, large deformations might occur. It is well understood from the reported works that the response is different in case of combined axial and lateral loading. Analytical investigations (Davisson, 1965; Ramasamy, 1974; Goryunov, 1975) suggest an increase in lateral deflection whereas the experimental investigations (Bartolomey, 1977; Sarochan & Bykov, 1976; Karasev et. al. 1977), suggest a reduction in lateral deflection due to the presence of vertical load. The possible reasons for this contradiction are to be addressed based on vigorous analyses by numerical methods.

In view of the above stated issues, this investigation on the interaction between vertical and lateral loads on the response of piles in homogeneous soft clay has been taken up using the finite element program GEOFEM-3D. This paper presents the results of three-dimensional finite element analyses of piles in homogeneous soft clay under different loading conditions such as individual lateral and combined vertical and lateral loading. Since the lateral response of piles is more critical and interesting for the design engineers, as piles are not often structurally designed to sustain significant lateral loads, the analysis mainly focuses on the effect of vertical load on the lateral load response of piles in soft clay with reference to key parameters influencing the behavior.

2 PRESENT 3-D FINITE ELEMENT MODEL

In the present analysis, the finite element program GEOFEM3D developed by the authors was used to study the interaction between pile and soil under combined axial and lateral loading. In the model, pile and soil continuum are divided into number of nodes and elements. Fig. 1 shows the schematic 3-d finite element mesh discretization. Solid 20-noded isoparametric brick elements have been used to represent the pile and the soil continuum. The interface between the pile-soil has been modeled using 16-node joint elements of zero thickness. All the nodes on the lateral boundaries are restrained from moving in the normal direction to the surface representing rigid, smooth lateral boundaries. The nodes on the bottom surface are restrained in all the three directions representing rough, rigid bottom surface. The finite element meshes consisted of approximately 7,000 nodes and 1,450 20-node isoparametric brick elements. The pile has been considered as linear elastic material and the homogeneous soil has been treated as elastic-perfectly plastic materials

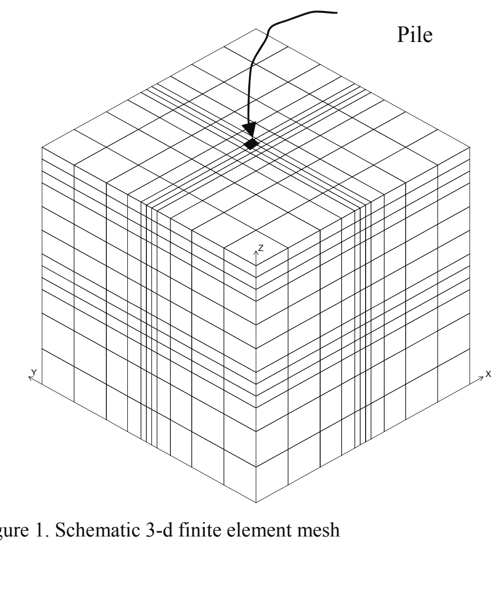

Figure 1. Schematic 3-d finite element mesh

based on Drucker-Prager constitutive model with non-associated flow rule. The analysis scheme, stages of analysis, constitutive model, incremental finite element procedure adopted etc. have been described in more detail by Rajagopal et al. (2003).

3 PARAMETRIC STUDIES

Since, allowable lateral deflection governs the design criteria in most of the cases, the results are presented and discussed in this paper in terms of load vs. deflection response of piles under pure lateral loads and combined vertical and lateral loads. Accordingly, series of three-dimensional finite element analyses have been performed by using GEOFEM3D program for single pile in homogeneous soft clay and subjected to pure lateral load as well as combined vertical and lateral loads. For the sake of analysis, the pile has been assumed to be 1200 × 1200mm square pile with a length of 10 m and made of M25 grade of concrete with deformation modulus of 25,000 MPa and Poisson's ratio of 0.15. The homogeneous soft clay soil is assumed to have cohesive strength (c_u) of 40 kPa; Young's modulus of 15,000 kPa and Poisson's ratio of 0.49. The analyses were conducted for both free head and fixed head conditions. The pile head was allowed to rotate during lateral load application for the free head case while it is not allowed to rotate for the fixed head case by preventing the vertical deformation of pile head nodes. The numerical results obtained from this investigation with reference to various parameters are presented as follows.

3.1 Influence of method of loading

In the present analysis, the combined loading on pile is applied in two different ways, simultaneously applied vertical and lateral loads (SAVL) and vertical load prior to lateral load (VPL). In the first case (SAVL), both vertical and lateral loads are applied simultaneously in incremental form in each load step. In the second case (VPL), the loads are applied in two stages. In the first stage, only the vertical loads were applied in number of load steps and then in the second stage, the lateral loads were applied in small increments while keeping the vertical loads constant. The ultimate vertical load (V_{ult}.) of single pile has been evaluated a priori by numerical analysis. For the combined vertical and lateral load analysis, the lateral load analyses have been performed with a vertical load equal to $0V_{ult}$., $20\%V_{ult}$., $40\%V_{ult}$., $60\%V_{ult}$., $80\%V_{ult}$ $100\%V_{ult}$. The analysis in lateral direction was performed by applying equal lateral displacements to pile head and the reaction forces were monitored to calculate the lateral force acting on the pile.

Figs. 2 and 3 show the lateral load vs. deflection response for the pile under SAVL and VPL cases respectively. In these figures, the curves indicated by $0\%V_{ult}$ represents the case of pure lateral load and the rest of the curves indicate the influence of vertical load ($20\%V_{ult}$ to $100\%V_{ult}$) on the lateral load response of pile. It is seen from Fig. 2 that the influence of vertical load for SAVL case is rather limited i.e. almost nil at small lateral load level and it is more prominent at higher lateral load level. On the other hand, in VPL case, as seen from Fig. 3, that the influence of vertical load is significant at all load levels.

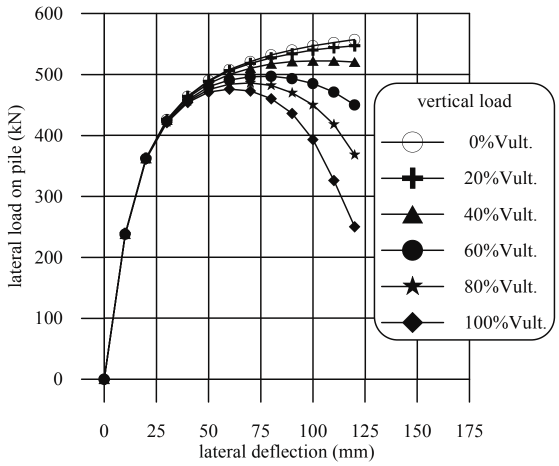

Figure 2. Lateral load-deflection relationship of free-headed pile for SAVL case.

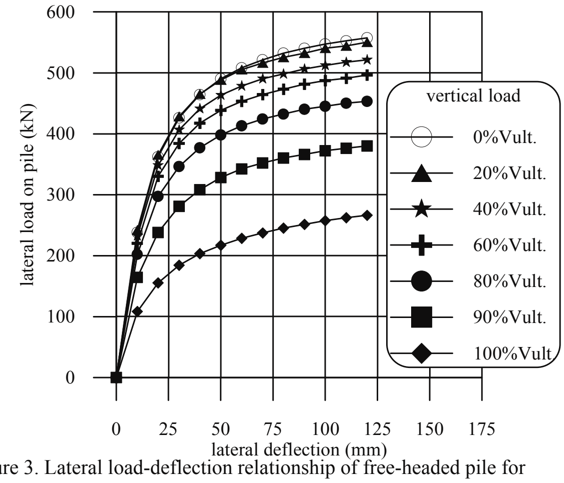

Figure 3. Lateral load-deflection relationship of free-headed pile for VPL case.

Also, it is commonly observed in both the cases that the lateral capacities for a specified deflection decrease as vertical load increases. Since the influence of vertical load on the lateral response of pile is more significant in VPL case, the results related to VPL case only are discussed here after. The VPL case is more practically relevant as the piles in harbour structures are subject to permanent vertical loads and are subjected to lateral loads only during ship berthing operations.

3.2 Influence of vertical load

From the above Fig. 3, the normalized lateral load capacities (H*, i.e. $H^*=H/c_uB^2$, where 'H' is the lateral load capacity of pile) have been estimated for different levels of deflections and are plotted against the vertical load variation in Fig. 4. From the figure, it is clear that the influence of vertical load on the lateral load capacities is nominal at small vertical loads ($0\%V_{ult}$. to $20\%V_{ult}$.) and then considerable decrease is noticed for vertical loads from $20\%V_{ult}$. to $80\%V_{ult}$ followed by an exponential decrease in lateral load capacities at greater vertical loads. This has been commonly observed at all deflection levels.

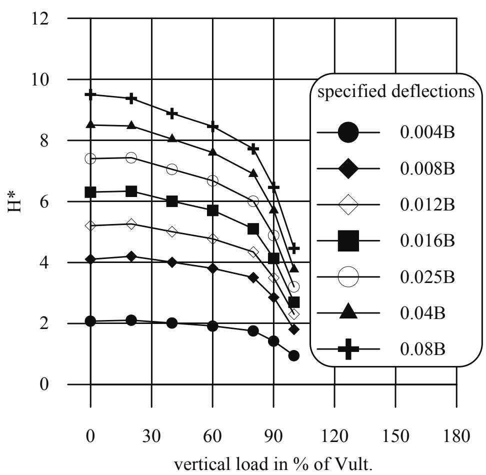

Figure 4. Normalized lateral load capacities at different allowable lateral deformations

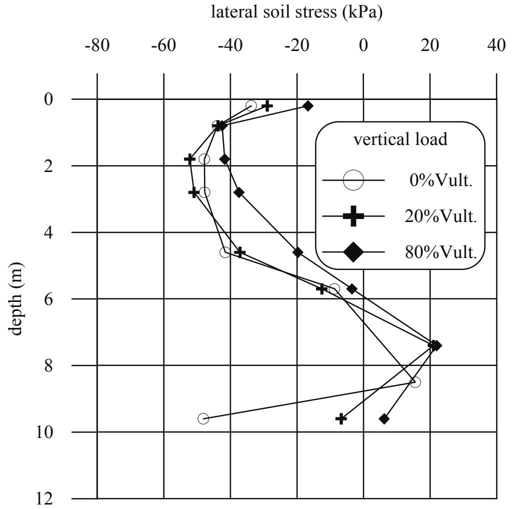

Figure 5. Variation of lateral soil stresses in front of free-headed pile

For the sake of better understanding the reduction of lateral load capacity, the variation of lateral soil stresses in front of free-head pile for vertical load levels of 0%V_{ult}, 20%V_{ult} and 80%V_{ult} and corresponding to a specified deflection level of 0.008B from the VPL cases are presented in Fig. 5. It is to be noted from the figure that the lateral soil stresses in front of pile are almost same for the case of 0%V_{ult} and 20%V_{ult}, and reduced under the influence of greater vertical loads (80%V_{ult}), thus indicating that the lateral soil stress along the depth also reduce with increase in vertical load. This substantiates the phenomenon observed for load deflection response curves as discussed in previous section through Figs. 2 and 3.

3.3 *Influence of L/B ratio*

The results presented so far are based on an assumption that the pile is rigid. However, in order to decide whether a pile would behave rigid or flexible, it is essential to study the influence of L/B and to arrive at limiting values of L/B on the influence of vertical loads. Figure 6 shows the influence of L/B ratio on the normalized lateral load capacities for a specified deflection level of 0.004B. The combined load shown in the figure refers to normalized lateral load capacities for a specified deflection level of 0.004B. The combined load shown in the figure refers to a particular vertical load (60%V_{ult}). It is noted from the curves that the lateral load capacity of piles decrease under the influ-

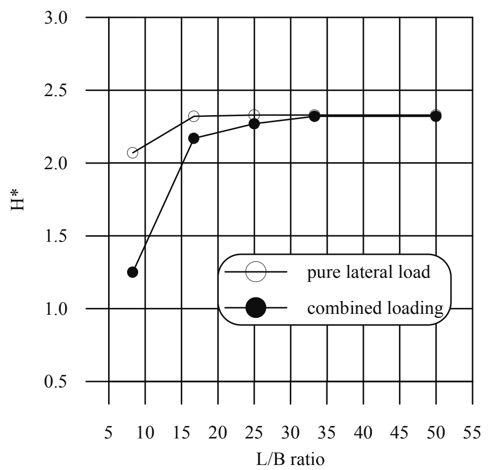

Figure 6. Lateral load capacities of piles under the influence of L/B

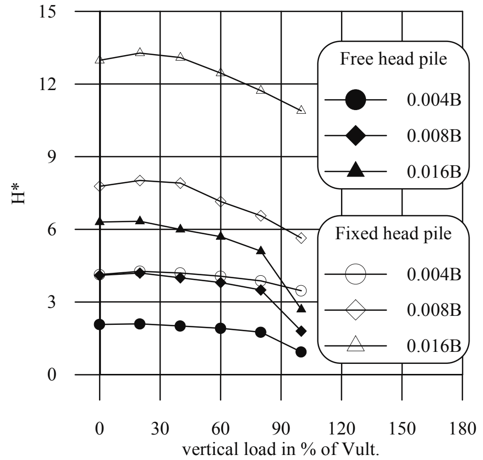

Figure 7. Normalized lateral load capacity under influence of vertical loads with reference to free and fixed head piles

ence of vertical loads at smaller L/B ratios up to say 10-20 and beyond these values of L/B influence is rather limited. For L/B ratios more than 30, the influence of vertical load is almost nil. Similar behavior has been observed for other vertical loads also. Thus, it can be inferred that the long flexible piles can be designed for pure lateral loads only irrespective of presence of any vertical load. Anagnostopoulos and Georgiadis (1993) based on their experimental analysis of long aluminium piles (L/B = 50) in soft clay also concluded that the influence of vertical load on lateral response is limited.

3.4 *Influence of Pile head fixity*

From the lateral load deflection curves, the normalized lateral load capacities ($H^*=H/c_uB^2$) have been assessed for different deflections of both free headed and fixed headed piles and are plotted against vertical load variation as shown in Fig.7. From the figure, it is commonly observed in both the cases that lateral load capacities decrease under the influence of vertical load. In order to understand the influence of vertical load on the pile head fixity, the lateral load capacities estimated for different deflections are compiled in Table 1. The percentage reduction in capacity over pure lateral load case is also given in the same table. From the table, it is clear that the influence of vertical load is almost within the range of –3 to +10 for both free head and fixed head conditions for small vertical loads (upto 60%V_{ult}). However, with the increase in the vertical load, the reduction in capacities is more or rather the influence is observed to be more in case of free headed piles than fixed headed piles. It is well-recognized fact that the capacities of piles under pure lateral loads are more in case of fixed head piles than free head piles due to restrained head condition. Besides, from the present observations, it can be inferred that even under the influence of vertical loads, the head restraint is playing a vital role in increasing the lateral load capacities at different allowable lateral displacement limits.

4 CONCLUSIONS

The numerical model based on three-dimensional finite element analysis described herein investigated the effect of vertical load interaction on the lateral load-deflection response of piles in soft clay with reference to some of the key parameters, viz., the vertical load level, sequence of loading, L/B ratio, pile head fixity conditions. The main conclusions that could be drawn from this investigation are as follows:

Table 1. Influence of vertical load on the normalized lateral load capacities (H*) of free and fixed-headed pile

Vertical load in % of Vult.	Lateral load capacity at 0.004B deflection		% reduction over pure lateral load case (0.004B)		Lateral load capacity at 0.008B deflection		% reduction over pure lateral load case (0.008B)		Lateral load capacity at 0.016B deflection		% reduction over pure lateral load case (0.016B)	
	Free head	Fixed head	Free head	Fixed head	Free head	Fixed head	Free head	Fixed head	Free head	Fixed head	Free head	Fixed head
0	2.07	4.13	0	0	4.1	7.78	0	0	6.84	12.98	0	0
20	2.1	4.27	-1	-3	4.2	8.02	-2	-3	6.9	13.28	-1	-2
40	2.01	4.20	+3	-2	4.0	7.91	+3	-2	6.5	13.09	+5	-1
60	1.91	4.06	+8	+2	3.8	7.15	+8	+8	6.2	12.45	+10	+5
80	1.75	3.87	+15	+6	3.5	6.56	+15	+16	5.5	11.73	+20	+10
100	0.94	3.47	+55	+16	1.8	5.64	+56	+28	2.95	10.9	+56	+16

The vertical load has significant influence on the lateral response of piles. When both vertical and lateral loads are simultaneously applied (SAVL case), the influence of vertical load on the lateral response of pile is felt only at higher vertical load levels, whereas when the vertical load is applied prior to lateral loads (VPL case), the influence is noticed at all the load levels. The lateral capacities decrease and deflections increase under the presence of vertical loads in general and it is more prominent at higher vertical load levels. This could be mainly attributed to the reason that in case of soft clays under vertical loads, the soil gets initially compressed and when the lateral load is applied, the corresponding net passive resistance will be less than the expected passive resistance. The initial compression increases with respect to the amount of vertical load. This has also been illustrated through the lateral stress variation plots along the depth for low and high fractions of vertical load (Figure 5).

The influence of vertical loads on the lateral response is felt only upto a certain limiting value of L/B (15 to 30) for a specified lateral deflection and beyond this values, the piles can be designed as flexible piles under pure lateral loads irrespective of the presence of vertical loads. The influence of the vertical load is significant in the L/B range of up to 15. As most of the piles installed on land fit in to this category, it is very important to consider this aspect for onshore piles. On the other hand, the piles installed in offshore structures tend to be very long for which the interaction effects can be expected to be minimum.

Fixed head piles offer more resistance to lateral loads in general. The current results show that this is true even in the presence of vertical loads.

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