BEHAVIOUR OF ROCK SOCKETED SHORT PILES UNDER LATERAL LOADS

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ABSTRACT : The paper discusses the influence of the length of rock socketing on the behaviour of short piles under lateral load based on a three-dimensional finite element analysis. In the analysis, pile is treated as linear elastic material and the soil as well as rock is treated as elastic-perfectly plastic materials based on Drucker-Prager constitutive models with non-associated flow rule. The pile behaviour in a continuum consisting of a homogeneous soil layer overlying a rock mass layer has been analyzed to investigate the effect of socketing of pile into rock by varying the socket lengths from 0 to 3 times the width of pile. The numerical results obtained from the analyses have been presented in terms of the lateral load-deflection relationships and bending moments along the length of pile with reference to various pile socket lengths. The minimum socket lengths within which maximum beneficial effect under lateral loads can be achieved in both free headed and fixed headed piles have also been proposed.

1. INTRODUCTION

Piles under lateral loads in a homogeneous soil media itself is a complex soil-structure interaction phenomenon and it gets further complicated in case of piles socketed into rock mass. For a pile socketed into the rock, a large percentage of the pile load capacity is derived from the side resistance offered along the pile length. Accordingly, the current practice is to socket the piles into the rock over a length of at least one to four times the pile diameter (IS 14593: 1998) depending on the type of rock strata (softer the rock, more is the socket length) to generate the desired load capacity. However, when the end bearing is in hard rock formations, drilling large diameter holes for such long lengths may involve in considerable time and expenses. Some times, it may not even be possible to embed the piles in hard rock to such large depths. The behaviour of such piles under lateral loading is of interest to design engineers. Especially, the quantities such as the maximum lateral deflection and the bending moment along the pile section are of interest to the designer. A few researchers (Gabr 1993) reported that in practice it has been customary to use the techniques developed for laterally loaded piles in homogeneous soils [Matlock and Reese (1960), Broms (1964)] to solve the problem of rock socketed shafts under lateral loads also. However, the response of rock socketed short pile is certainly different than the pile embedded in homogeneous soil because of the difference in the possible failure mechanisms. Reese (1997) developed a p-y curve method for the analysis of single pile in weak rock subjected to lateral loading considering the non-linearity of the rock mass surrounding the pile by assuming a series of soil/rock springs along the length of the pile. However, the p-y curve method uses empirically computed spring constants, which are not reliable material properties and also ignores the interaction between pile-rock/soil-rock as well as rock-rock contacts in soil and rock continua. Only a few investigators [Zhang et al. (2000)] have proposed methods of analyses and design of laterally loaded rock-socketed shafts treating the rock mass as an elastic continuum. From the above works, it has also been noted that the maximum lateral deflection mainly governs the design rather than the ultimate lateral capacity of the piles. In view of the above, this paper presents and discusses some of the interesting results from a full 3D finite element analysis carried out to investigate the behaviour of rigid piles socketed into hard rock to various lengths. The minimum socket lengths within which maximum beneficial effect under lateral loads can be achieved have also been proposed.

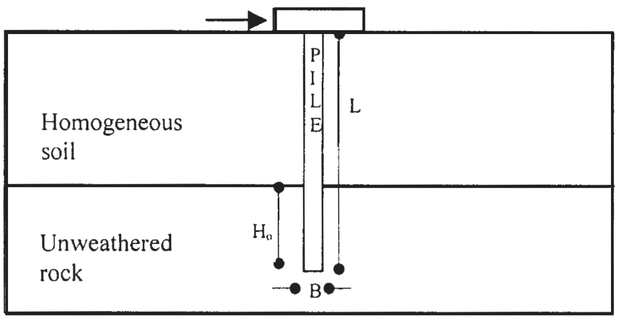
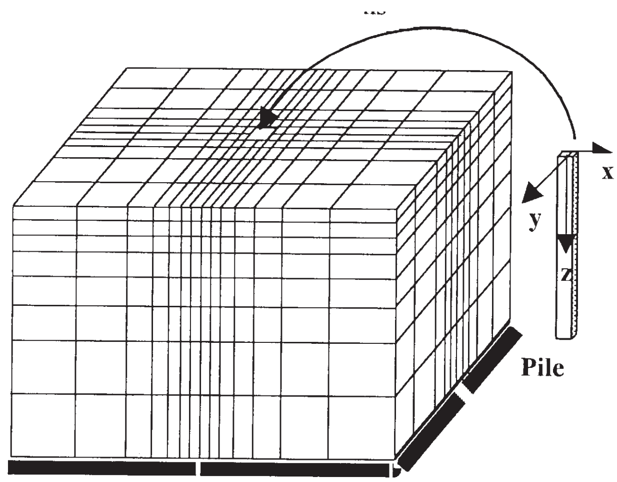


Fig.1. Schematic of Pile under lateral load and socketed into the rock

2. PRESENT FINITE ELEMENT MODEL

Fig.1 shows the schematic definition of problem considered for the analysis. The pile has been assumed to pass through an uniform homogeneous sandy soil layer followed by an unweathered rock.

The socket lengths of pile into the rock (Ho) have been varied from 0 to 3 times the width of pile (B). The thickness of the rock layer has been considered to be much larger than the pile socket length. In the present analysis, the finite element program GEOFEM3D has been used to study the effect of socket length on the response of short piles under lateral loads. Fig. 2 shows the 3D finite element mesh used for the analysis. Solid 20-noded isoparametric brick elements have been used to represent the continuum. The interface between the pile-soil as well as pile-rock has been modelled 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. All the nodes on the bottom surface are restrained in all the three directions representing rough, rigid bottom surface. The finite element mesh consisted of approximately 7,000 nodes and 1,450 elements. The mesh has been discritized finely around the pile to account for the steep stress gradient near the pile-soil and pile-rock interface.



The pile has been considered as linear elastic material and the homogeneous soil as well as rock have been treated as elastic - perfectly plastic materials based on Drucker-Prager constitutive model with non-associated flow rule. The yield surface for this model has the form $F=\alpha J_1 + \sqrt{J_{2d}-k}$, in which J_1 is the first invariant of the stress tensor, J_{2d} is the second invariant of the deviatoric stress tensor and α, k are the material constants related to the angle of internal friction (ϕ) and the cohesive strength of the materials (c) as follows:

$$\alpha = 2 \sin\phi / \sqrt{3}(3+\sin\phi) \quad \text{-----------------} \quad (1)$$

$$k = 6\, c \cos\phi / \sqrt{3}(3+\sin\phi) \quad \text{-----------------} \quad (2)$$

The analysis scheme, stages of analysis, incremental finite element procedure adopted etc. have been in general as brought out in Rajagopal et al. (2003).

3. PARAMETRIC STUDIES

Series of three-dimensional finite element analyses have been performed on rock socketed single short piles under lateral loads by using GEOFEM3D program. The analyses have been performed on both free and fixed head pile conditions under lateral loads.

For the sake of analysis, the pile has been assumed to be of M25 grade concrete with deformation modulus of 25000 Mpa and the poisson's ratio of 0.15. The length and width of square concrete piles have been selected in such a way that the pile behaves like a short rigid pile, i.e., the relative stiffness of pile and soil ($K_r = E_pI_p/E_nL^4$) is greater than 0.01 as suggested by Poulos and Davis (1980); in which E_pI_p is the flexural rigidity of the pile section and E_n is the average normal soil/rock modulus along the embedded length 'L'. The unweathered rock is assumed to have an uniaxial compressive strength of 750 kPa; deformation modulus of 50000 Mpa and poisson's ratio of 0.26.

4. RESULTS AND DISCUSSION

4.1 Load-deflection behaviour of pile socketted in rock

Fig. 3a & 3b shows the lateral load-deflection relationships for free head and fixed head piles with reference to various socket lengths. The load-deflection curve corresponding to Ho/B = 0.0 represents that of a pile with its tip just resting on the rock. It can be seen from the curves that the lateral deflections decrease with the increase in socket length. This behaviour is more prominent at higher lateral loads. Also, for a specified deflection, piles socketed into rock carry greater loads when compared to those just resting on rock (Ho/B= 0.0). Similar trends have been observed for both free head and fixed head piles. However, the deflections are quite sensitive to pile head fixity and these were quite low in case of fixed headed piles in comparison to free head piles for all the socket lengths.

Figs. 4a & 4b show the lateral capacity of free and fixed head piles for specified lateral deflections computed from the load-deflection plots. It can be seen from the curves that the lateral response of piles increased with increase in socket lengths upto a certain socket length and beyond which it is more or less constant. These limiting values are around 0.5B to 1.2B for 5mm to 20mm lateral deflections in free head piles while these are 0.5B to 0.8B for 3mm to 7mm lateral deflections in case of fixed head piles. Thus, it is very much clear that the maximum socket length required is a function of the allowable deflection and not necessarily be a constant value all the time.

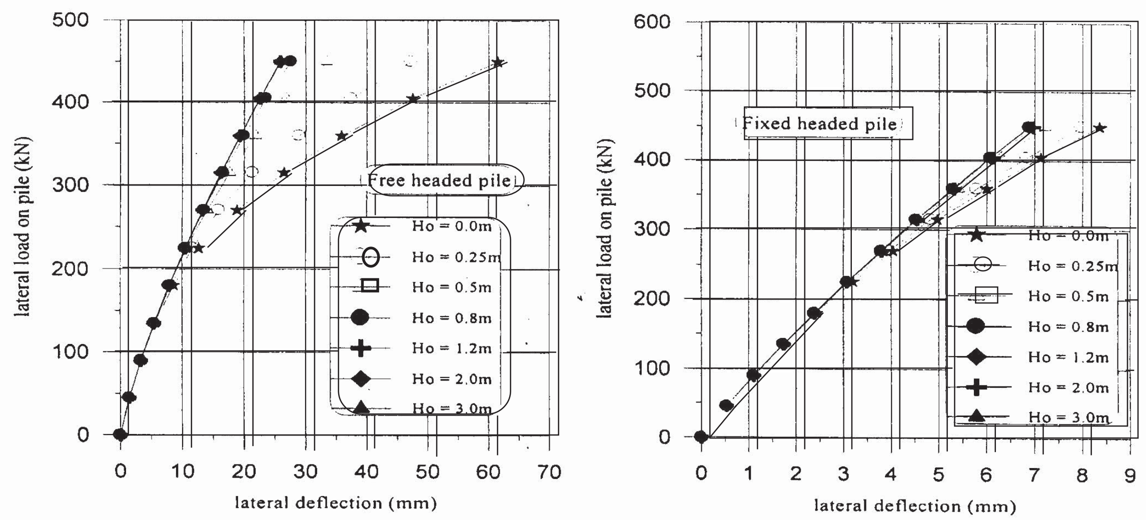


Fig.3 (a) & 3(b) Lateral load-deflection response of piles for various socket lengths

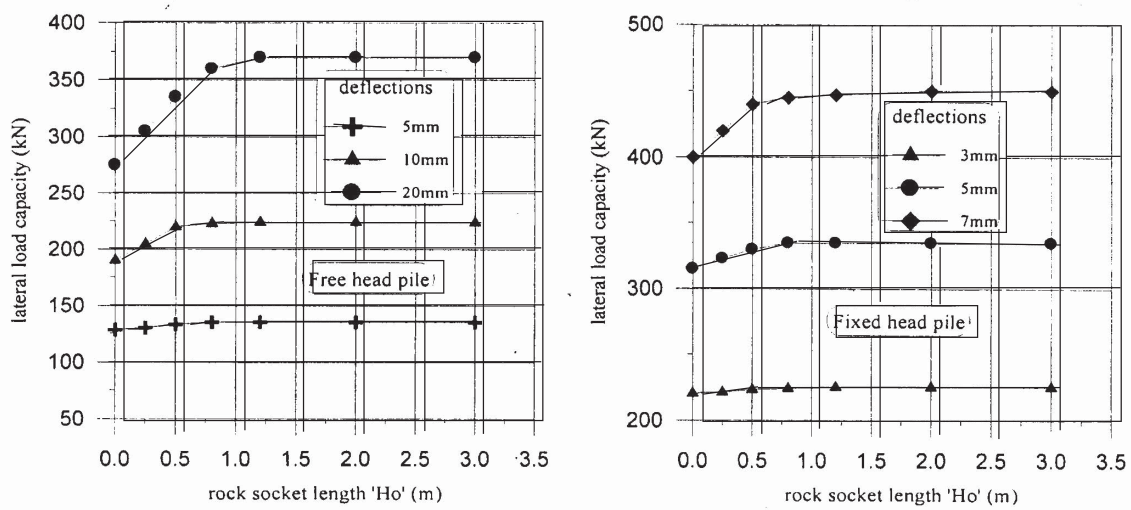


Fig. 4(a) & 4(b) Influence of rock socket lengths on lateral capacities of piles

The maximum lateral deflection vs socket length plotted for a specific load as shown in Fig.5 also substantiate this phenomenon. It can be seen from the plot that the maximum lateral deflections also become constant beyond a certain socket length. The socket length has very less significance in case of fixed head piles, because of the head fixity.

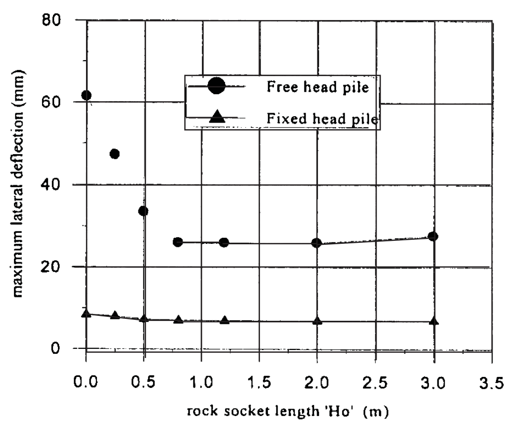


Fig. 5 Influence of rock socket lengths on maximum lateral deflection of piles

4.2 Bending moment variations along the length of pile socketted in rock

The bending moments along the length of the pile section have been assessed using the well known flexural equation $f_y = (M/I).y$ in which, f_y is the flexural stress and y is the distance from the neutral axis. Fig. 6a and 6b shows the typical bending moment variations along the length of free head and fixed head piles for various socket lengths. It can be noted from these curves that the maximum bending

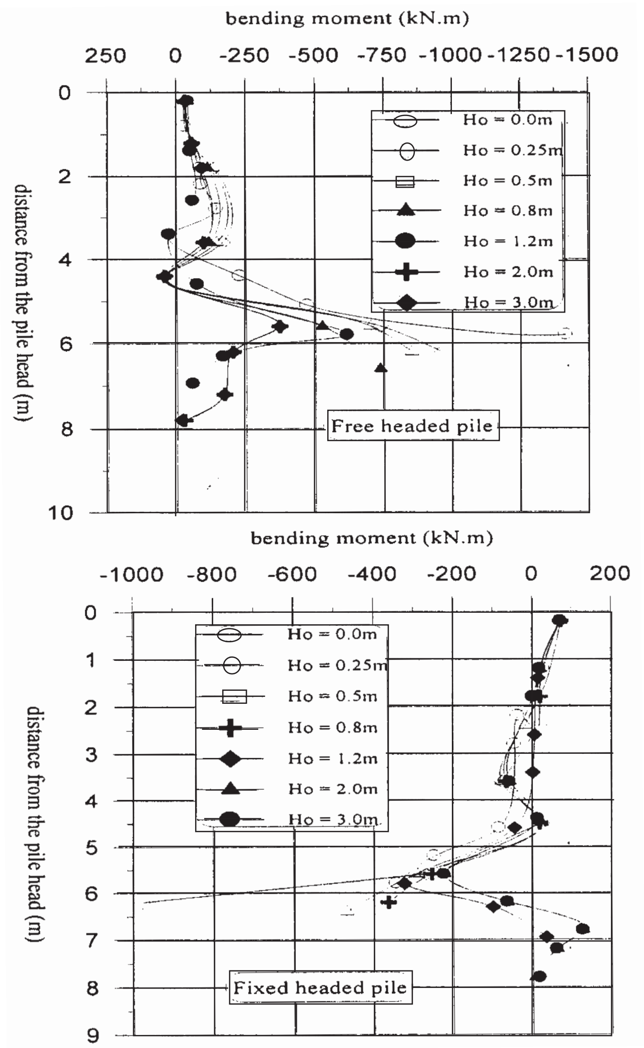


Fig. 6(a) & 6(b)
Bending moment variations along the length of pile

moments decreased with increase in socket lengths and also the point of maximum moment observed to be around 5.6m to 6.2m from the pile head, which is almost nearer to soil-rock interface. Besides, two points of contra flexure were observed in case of fixed head piles, which are mainly attributed to the fixity conditions both at top as well as bottom of the piles.

5. CONCLUSIONS

Based on the study, the following conclusion could be drawn:

The lateral load capacity increases and the deflection decreases when the piles are socketted into rock upto certain lengths and beyond which the behaviour is almost constant. These limiting lengths are 1.2B for free headed piles and 0.8B for fixed headed piles from the capacity point of view and the 0.8B for free headed piles and 0.5B for fixed headed piles from maximum deflection point of view. This gives an indication that it is not essential all the time to embed the pile into hard rock for a standard depth and even a small length of socketing of around 0.5B to 1.0B is sufficient enough to cater for the lateral loads and deflections. The maximum bending moments in piles are likely to occur at the soil-rock interface for free headed piles. Besides, it is also dependent on head fixity in case of fixed head piles.

The study presented herein is based on a full 3D finite element analysis, but for a set of parameters only and thus it needs further verification incorporating the effect of different pile-soil-rock combinations for making generalized guidelines.

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