NUMERICAL ANALYSIS OF ROCK SOCKETED PILES UNDER LATERAL LOADS

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ABSTRACT: The current field practice is to socket the end bearing piles in hard strata over a length of at least three times the diameter of the pile. However, when the end bearing is in hard rock formations, drilling large diameter holes for such long lengths may involve considerable time and expenses. This paper examines the influence of the length of socketing on the performance of piles subjected to lateral loads based on a numerical study. A full 3-dimensional analysis of square piles subjected to lateral loads was performed using the finite element program GEOFEM-3D. In the analysis, pile is treated as linear elastic material and the soil/rock as elastic-perfectly plastic based on Drucker-Prager constitutive model. Pile behaviour in a continuum consisting of a sandy soil layer overlying a rock mass layer was analyzed to investigate the effect of pile socketing into rock by varying the pile socket lengths from 0.0B to 3.0B. Square concrete piles with breadth of 1.0m and lengths of 6.0m and 15.0m representing short rigid and long flexible conditions respectively have been analyzed under pure lateral loads. The results obtained from the analyses have been presented in terms of the lateral load-deflection relationships, maximum lateral deflections and bending moments along the length of pile with reference to pile head fixity condition and pile socket length (H_o). The results show that the response of both short and long piles socketed into the rock is different from that of a pile embedded in a homogeneous soil. Based on the analysis, the socket lengths within which maximum beneficial effect under lateral loads can be achieved have also been proposed.

Key words: Pile, Rock Socketing, Finite Element analysis, Drucker-Prager Constitutive Model, Lateral Deflection, Bending Moments.

INTRODUCTION

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 piles with large lateral loads are embedded into hard strata by a length equal to at least 3 times the pile diameter (as prescribed in the relevant codes) to generate the required load capacity, i.e. a one meter diameter pile should at least be embedded by 3.0m, which is highly expensive and time-consuming and also in many field cases, it may not 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 developed within the pile section are of interest to the designer.

Matlock and Reese (1960); Broms (1964) gave generalized solutions for the laterally loaded piles embedded in homogeneous cohesive and granular soils. Although, these were published many years ago, these methodologies are still popular among design engineers due to lack of other information. A few researchers (Amir 1986, Gabr 1993) reported that in practice it has been customary to use the techniques developed for laterally loaded piles in homogeneous soil to solve the problem of rock-socketed shafts under lateral loads also. However, the response of short embedded pile socketed into the rock is 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 [Carter and Kulhawy (1992); 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 all the above works, it can be noted that the design criterion in the majority of the cases is not the ultimate lateral capacity of the shafts, but the maximum deflection of the shafts.

In view of the above stated issues, the present paper presents and discusses some of the interesting results from a full 3D finite element analysis carried out to investigate the behaviour of rigid and flexible piles socketed into hard rock to various lengths.

NUMERICAL MODEL

Fig. 1 shows the schematic definition of problem considered for the analysis. In the analysis, the pile was considered as linear elastic material and the soil/rock as elastic- perfectly plastic material based on Drucker-Prager constitutive model.

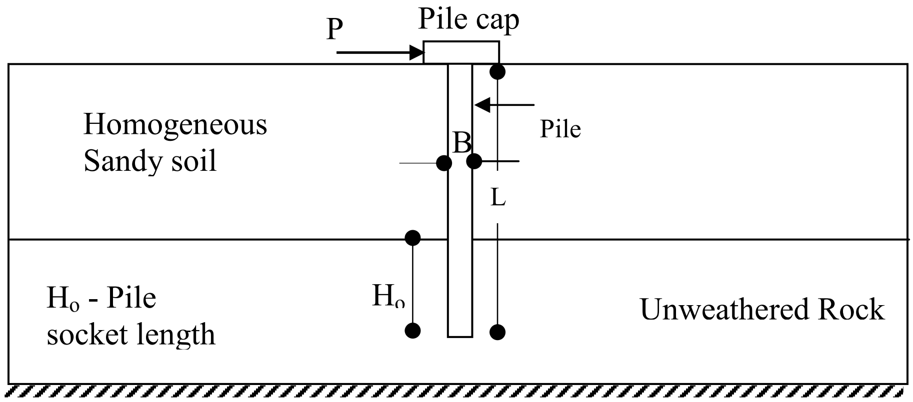

Figure 1. Schematic of single pile socketed into the rock subjected to lateral load

In the present analysis, the finite element program GEOFEM3D has been used to study the interaction between pile and soil/rock under lateral load. Fig. 2 shows the schematic 3D finite element mesh used for the analysis. 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 meshes consisted of approximately 7,000 nodes and 1,450 20-noded isoparametric brick elements. The interface between the pile and soil/rock was modelled using 16-node joint elements of zero thickness. The finite element mesh was discretised finely around the pile to account for the steep stress gradient near the pile/soil interface.

Pile Model

The solid 20-node brick element was used to model the piles, which is treated as linear elastic material. The pile was assumed to be made of M25 grade of concrete and the Poisson's ratio was assumed as 0.16. The short and long lengths of square concrete piles were taken as 6.0m and 15.0m respectively. The width of the pile was assumed as 1m, same for both short and long piles. The relative stiffness between the pile and soil is defined using the factor K_r as follows:

$$K_r = E_pI_p/E_nL^4 \qquad \text{------------------------} \ (1)$$

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'. A pile is considered to be flexible if its relative stiffness K_r is less than about 0.01 (Poulos & Davis 1980). The relative stiffness value calculated for the short and long piles under consideration worked out to be 0.08 and 0.00205 respectively, which shows that these piles can be treated as rigid and flexible piles.

Both free head and fixed head conditions were considered at the pile head. The fixed head piles will not rotate at the pile head because of the stiff pile cap. The same was approximately simulated in the analysis by enforcing

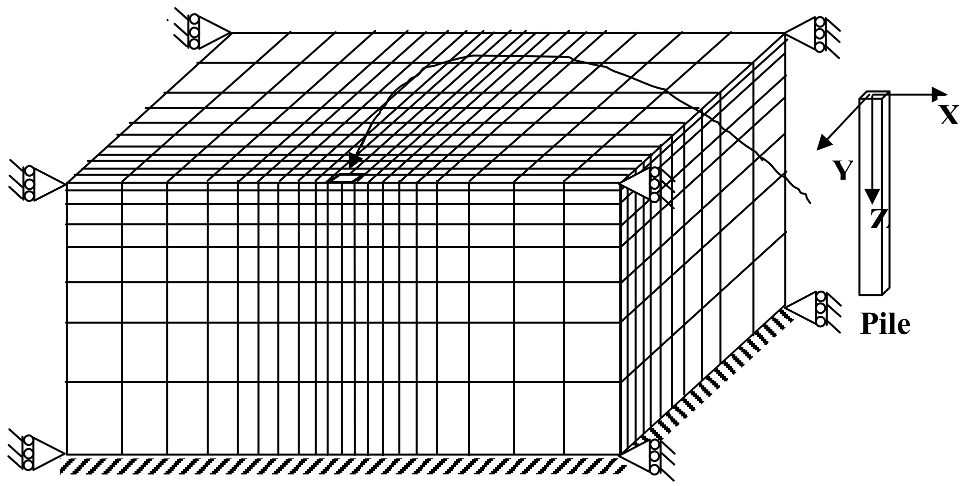

Figure 2. Three-dimensional finite element mesh

equal vertical deformation of all the nodes at the pile head, while they move freely in the lateral direction. On the other hand, the nodes on the free head pile were left free to move in the vertical direction so that the pile head can undergo rotational deformations under the lateral loads.

Soil/Rock Model

The behaviour of the soil/rock has been idealized using the Drucker-Prager perfectly plastic constitutive model with non-associated flow rule. The Drucker-Prager model can be approximated to the well known Coulomb criterion by a simple smoothing function. 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:

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

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

During the plastic state, the constitutive matrix was first formed based on the current tangent modulus and Poisson's ratio for elastic state and then a correction was applied to obtain the elastic-plastic constitutive matrix. The stresses are corrected back to the yield surface along the flow direction defined by the dilation angle (ψ) as described by Nayak & Zienkiewicz (1972). The resulting plastic volumetric strains are more realistic than those computed using the associated flow rules ($\psi = \phi$)

Analysis Scheme

The analyses were performed in two stages. In the first stage, the self-weight of the soil was applied with a Poisson's ratio equal to $K_o/(1+K_o)$ in which K_o is the lateral at-rest earth pressure coefficient. Both the pile and soil elements were assigned the same material properties (Young's modulus, Poisson's ratio and unit weight) so as not to generate extraneous shear stresses. All the nodal deformations and strains in the elements were set to zero at the end of this stage of analysis. The external loads were applied during the second stage. During this analysis, the relevant properties for pile and soil were assigned to the corresponding elements.

The incremental finite element equilibrium equations considered are of the type shown in Equation 4 in which the load vector is expressed as the difference between the external load vector and the internal reaction force vector computed from the element stresses of the previous iteration. In which the 1st term on the RHS is the applied force

$$[K]_t \{\Delta u_i\} = \{P\}_{exti} - \Sigma [B]^T \{\sigma_{i-1}\} \quad (4)$$

vector and the 2nd term on RHS is the internal nodal force vector (reaction force vector). This analysis scheme allows for carrying forward any error in the out-of-balance force to the next iteration (or next load step) thus satisfying the global equilibrium at all the load steps.

In the analyses, lateral loads were applied in small increments consisting of several load steps with a maximum of 50 iterations. The iterations were continued at each load step until the norms of out-of-balance force and incremental displacements decrease to less than 0.5% or until 50 iterations are completed.

Series of three-dimensional finite element analyses were performed on single short rigid and long flexible piles socketed in rock subjected to lateral load by using GEOFEM3D finite element program. The analyses were performed both for free head and fixed head pile conditions subjected to lateral load. The analyses were performed with different lengths of pile socketing. For comparison purposes, the results are compared with the results obtained from the analysis of similar pile installed in uniform soil. The soil was assumed to have properties: c=0, ϕ=30°, E=20,000 kPa and Poisson's ratio of 0.30. The rock stratum was assumed to have the properties: c=750 kPa, ϕ=45°, E=50,000 MPa and Poisson's ratio of 0.26. The thickness of the rock layer was taken as much larger than the pile socket length. Here, all analyses with single piles were performed for the pile socketed into the rock by varying the socket length from 0.0B (pile just resting on hard rock) to 3B. The results obtained from the analyses have been discussed in details in the following sections.

RESULTS AND DISCUSSION

Behaviour of Piles in Homogeneous Soils

Fig. 3 shows the load – deflection relationship for piles embedded in uniform/homogeneous sandy soil with free head and fixed head conditions. It can be observed form the results that the response of the pile is highly

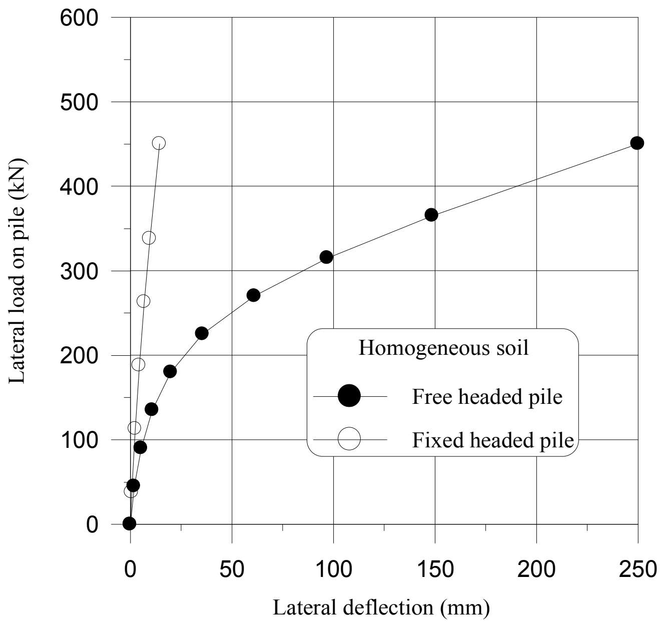

Fig. 3 Lateral load – deflection relationship of short rigid pile in homogeneous sandy soil

sensitive to the pile head fixity. For the same applied lateral load, the fixed head pile has undergone much smaller lateral deformation than the free head pile.

Load Deflection Behaviour of short rigid piles socketed in rock

Similar analyses have been performed for the short pile embedded into hard rock with the socket lengths varying from zero to 3 times the width of pile and by keeping the thickness of soil layer is constant i.e. 6m. Fig. 4 shows the relationship plots between lateral load and deflections for free head and fixed head piles with reference to various socket lengths. It can be seen from the curves that the lateral deflections decrease with the increase in socket length. Also, for a specified deflection, piles socketed into rock carry greater loads when compared to those embedded in uniform sandy soil or resting on rock i.e. without socketing into the rock (Ho/B

= 0.0). Similar trends were observed for both free head and fixed head piles, however, the deflections were quite low in case of fixed headed piles for all the socket lengths.

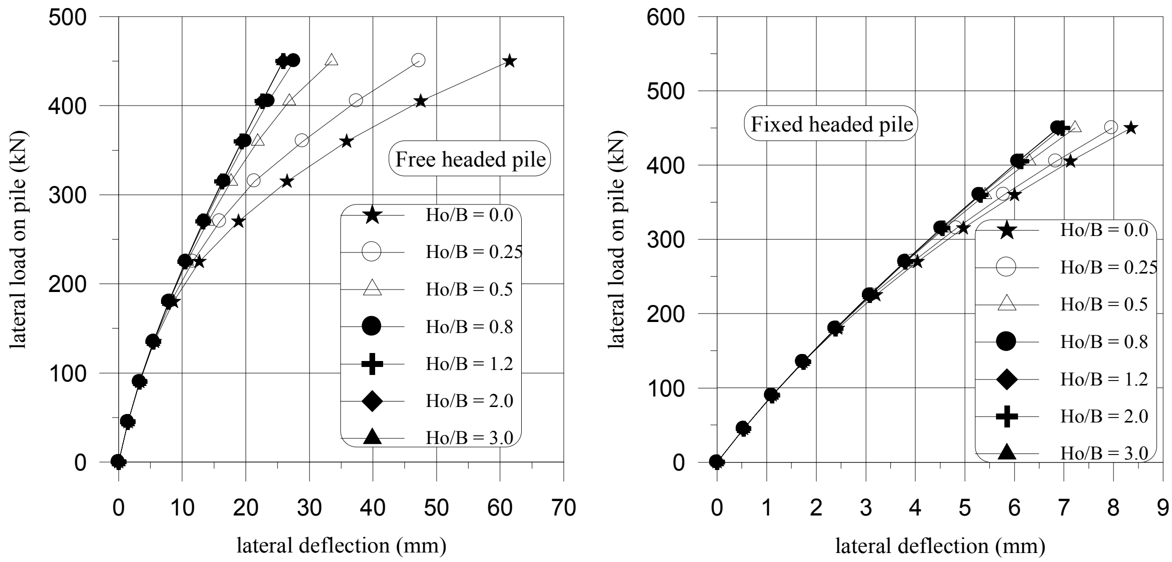

Figure 4 influences of rock socket lengths on the lateral response of free and fixed head piles

Fig. 5 shows the lateral load 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 is nonlinear for socket lengths in the order of 0.0B to 0.5B and beyond which it is more or less constant. Thus, the lateral load capacity of free headed piles increase with increase in socket lengths upto a certain length and beyond which no significant improvement is there. These limiting values are around 0.5B to 1.2B for 5mm, 10mm and 20mm deflections respectively for free head piles, while these are 0.5B to 0.8B for 3mm, 5mm and 7mm deflections respectively for fixed head piles. Further, it can also be noted from the curves that the influence of rock socket lengths on the lateral load capacities of piles are more significant for larger allowable deflections. This clearly gives an indication that it is not essential that all the time, piles should be socketed upto lengths of 3.0B.

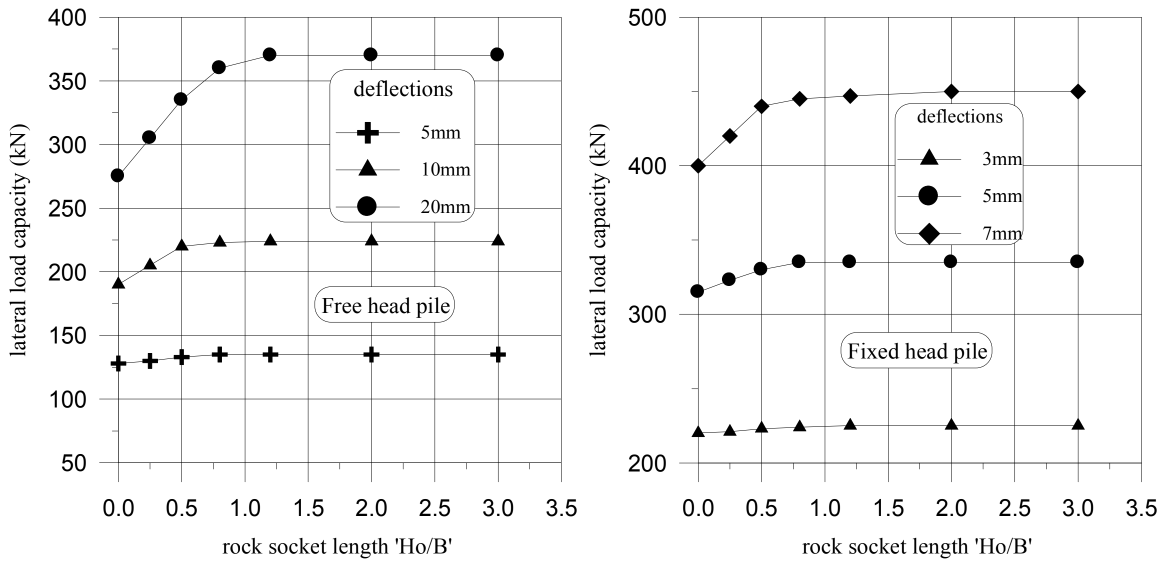

Figure 5 influence of rock socket length on the lateral load capacity of free and fixed head pile

This phenomenon has been further substantiated through the maximum lateral deflection values for free head and fixed head piles as presented in Fig. 6. The maximum lateral deflections of a free headed pile under 450kN load has been reduced from 60mm to 23mm by socketing the pile for a length of about 0.8B and there is no further reduction in deflection with the additional length of socketing. Similarly, in case of a fixed head pile, hardly there is any advantage by socketing the pile more than 0.5B.

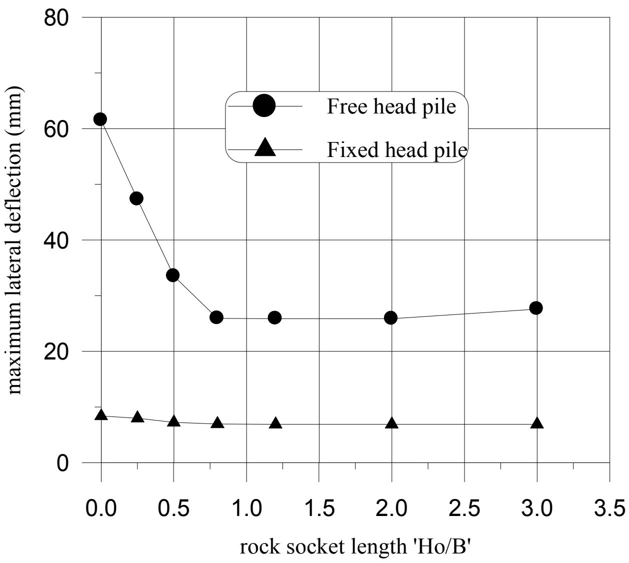

Figure 6 influence of rock socket lengths on the maximum lateral deflection of free and fixed head piles

Bending moment variation along the length of short pile socketed 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. 7 shows the variation in bending moment along the length of free head and fixed head piles. It can be noted from the curves that the bending moment variations in free head piles is almost similar within the top 4 m depth and beyond 4m, there is a significant variation for different socket lengths, which could be attributed to uniform soil properties within the depth of homogeneous sandy soil layers and beyond this depth, the maximum bending moments decreased with increase in socket lengths. However, the bending moments in piles became constant for socket lengths more than 2.0B. The depths of maximum bending moment were observed to be at points nearer to the soil-rock interface, which is around 5.6m to 6.2m from the pile head. Similar trends were observed even for fixed head piles with reference to various socket lengths. Besides, two points of contra flexure were observed in case of fixed head pile, which is mainly attributed to the fixity conditions both at top as well as bottom of the pile.

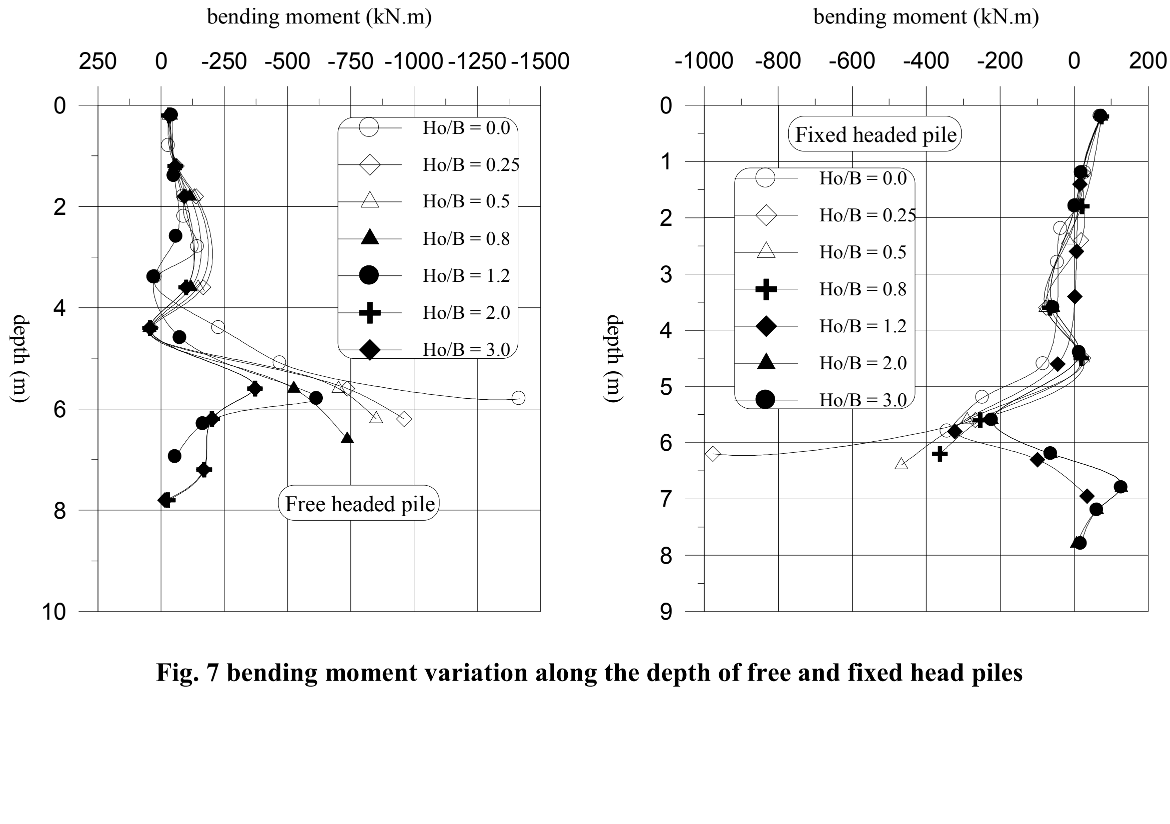

Fig. 7 bending moment variation along the depth of free and fixed head piles

Load deflection behaviour of long/flexible piles socketed in rock

To study the influence of pile stiffness, similar analyses were performed for long flexible free head pile having length and widths of 15m and 1m respectively. The thickness of soil layer is kept constant i.e. 15m and varying socket lengths. Fig. 8 shows the lateral load – deflection curves for long flexible piles with reference to

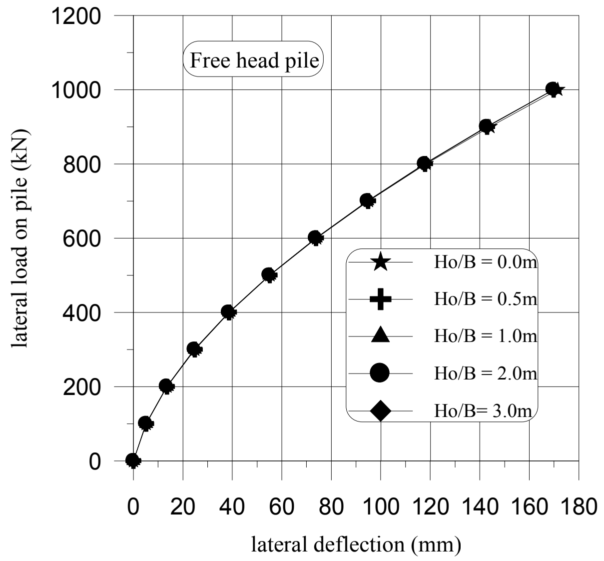

Fig.8 influence of socket lengths on the lateral response of long flexible pile

various rock socket lengths. Socket lengths were varied from 0.0B to 3.0B in steps of 0.5B as in the case of short piles. It can be seen from the curves that the influence of socket lengths is totally insignificant on the lateral response of long piles.

Bending moment variation along the length of long flexible pile socketed in rock

The bending moment variations along the length of long flexible pile have been assessed using flexural equation as discussed earlier. Fig. 9 shows the bending moment variation along the length of long flexible pile with reference to various rock socket lengths. It can be noted from the curves that the influence of socket lengths on the bending moment variation is more or less same for depths up to 5m from the pile head and considerable variation is seen from 5m to 10m depths and the influence of socket lengths is more conspicuous

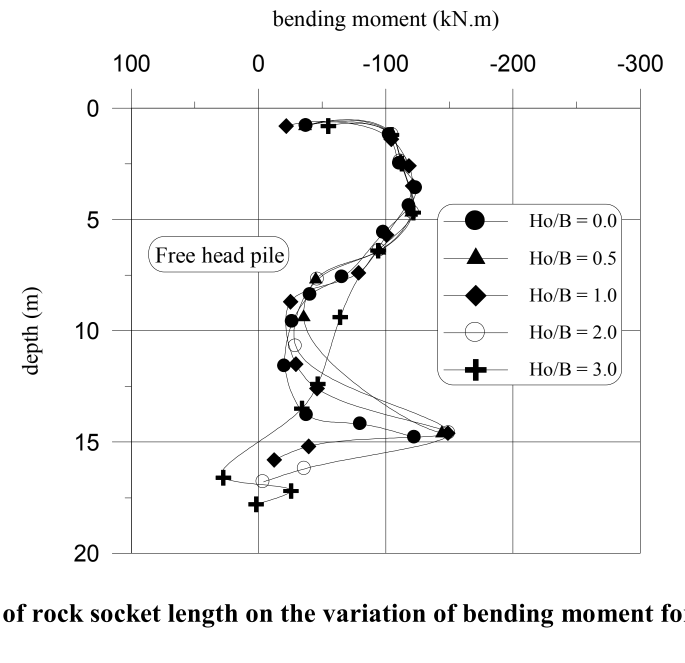

Figure 9 influence of rock socket length on the variation of bending moment for long flexible pile

below depths of 10m. This behaviour is attributed to uniform soil properties in the upper portion and the pile-rock interaction in the socketed portion. In this case also, the maximum bending moments are observed to occur closer to the soil-rock interface.

CONCLUSIONS

The behaviour of piles socketed into rock and subjected to lateral loads has been investigated though a 3-dimensional finite element model. The lateral load-deflection relationships along with bending moment variations have been presented to show the influence of varying rock-socket length and pile head fixity conditions. The following conclusions were offered from the above results and discussion.

The response of both short and long piles socketed into the rock is different from that of a pile embedded in a homogeneous soil and hence calls for a proper analytical/numerical modelling of the behaviour of piles socketed in rocks prior to their application in practice.

The lateral deflections of piles decreases with increase in rock socket length and the load capacity corresponding to specified deflection levels is almost constant beyond a socket length of 1.2B for free headed piles and 0.8B for fixed headed piles, which gives an indication that it is not essential all time to embed the pile into hard rock for a minimum depth of 3.0 times the width of the pile and even a small length of socketing of around 1.0B is sufficient enough to cater for the lateral loads.

In case of long flexible piles, the behaviour is mainly dependent on the flexural characteristics of the pile and least dependent on the socket length.

There is a considerable influence of rock socketing on the bending moment variations and the maximum bending moments in piles are likely to occur at the soil-rock interface for both free headed short and long piles. Besides, it is also dependent on head fixity in case of fixed head piles.

The study, in general, has provided a basis for restricting the socket length to a minimum possible distance into the rock and thus reducing the time and expenses for heavy drilling activity. However, the results need to be verified against good amount of field data.

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