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Estimation of lateral capacity of rock socketed piles in layered soil-rock profile

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Abstract

Large diameter rock socketed piles were preferred for the purpose of transmission of a huge volume of both vertical and lateral load from superstructure to a deeper depth safely without any structural defects. A series of experimental program was conducted on model pile for studying the behaviour of the rock socketed pile under static lateral load in a soil-rock layered profile system. The model piles were instrumented with displacement and force transducers for measuring the magnitude of the pile movement and load transferred by the pile. The experimental results showed that the rock socketed pile lateral capacity has significantly affected by the depth of embedment of the pile in soil and depth of rock socket. There was a considerable increase in the lateral capacity of the pile when the depth of socketing is three times the diameter of the pile into rock with a minimum embedment. In the 3D socketed piles, the lateral capacity of the pile is almost 18 times higher than the non-socketed piles. From the experimental study, it is also observed that when the piles socketed more in to the hard strata (rock), the depth of fixity increases and the lateral displacement reduces substantially.

Keywords: Socketed pile, Lateral capacity, Model pile, Pile instrumentation, Embedment depth and lateral deflection

Introduction

Heavy superstructures like bridge piers, elevated flyovers and offshore wind turbine structures supported by large diameter piles are often subjected to a significant amount of lateral loads. The lateral capacity of the pile mainly depends on the ultimate soil resistance and the stiffness of the pile. However, the deflection at the pile head should be within allowable limits under working load. Generally, large diameter piles were suggested for offshore wind farms and for heavy transmission towers in onshore in order to withstand the heavy loads from wind, waves, current and etc. In such a case, when the hard stratum is relatively in a shallow depth, the pile has to be socketed into the hard stratum to minimum depth of 1-3times the diameter (1D-3D) of pile based the compressive strength of the rock as per IS 14593-2003 [16]. Casting the pile in the hard stratum is a time-consuming process and requires heavy drilling equipment's for execution of the work, resulting in economic loss. However, the piles are expected to be supported by a considerable soil thickness before socketed into the hard stratum where the effect of soil embedment play a key role in the rock socketed pile capacity. Therefore, a systematic

experimental study is needed to understand the impact of soil embedment and depth of rock socketing on lateral capacity of piles especially on intermediate piles.

Extensive research has been carried out by Broms [3], Prakash and Kumar [26], Gandhi and Selvam [8], Muthukkumaran et al. [21], Begum et al. [1], Chandrasekaran et al. [5], Muthukkumaran [22] and Deendayal et al. [7] theoretically and experimentally to study the behaviour of the pile on clayey and sandy soil under lateral load. A limited number of instrumented load tests have been conducted for studying the response of pile socketed onto rock strata subjected to lateral load. Firstly, Carter and Kulhawy [4] presented parametric solutions from which closed-form solutions may be derived for various loading conditions and rock stiffness for the estimation of lateral deflection. Further, Reese [27] presented a p-y curve method for the analysis of single pile socketed onto weak rock and subjected to lateral loading. The non-linearity of the rock mass surrounding was considered by assuming a series of springs of soil or rock along the length of the pile. Ke Yang [19] conducted two field tests on piles and suggested a new method of deriving experimental p-y curves from load test results based on curve fitting techniques and presented the comparison of the method to existing methods. However, the method application of the method is limited due to requirement of field test results. Liang et al. [20] presented hyperbolic p-y criterion is developed based on both theoretical derivations and empirical equations derived from numerical finite element parametric analysis results. Very few researchers have considered the layered soil-rock profile thickness in the study of the pile under lateral load. Zhang et al. [31] proposed a non-linear continuum method to predict the load–displacement response of rock-socketed drilled shafts under lateral loads by treating soil/rock as an elastoplastic material which was not widely adopted. Haberfield and Collingwood [10] introduced a method to provide significant improvements in pile design, in respect both to optimisation of socket lengths and to reduction of risk based on field observations. Jin-Jian Chen et al. [18] presented a method considering a non-uniform shaft with diameter and/or flexural rigidity changing with depth and embedded in multiple layers of soil/rock masses. The method considers not only the yielding of the soil/rock mass but also the decrease in flexural rigidity of the shaft due to cracking. Rezazadeh and Eslami [28] presented a comparison of existing empirical formulae for the prediction of lateral shaft resistance. Singh et al. [29] explored the performance of the rock-socketed pile under combined loading. However, the existing methods have not considered various parameters simultaneously such as the embedment depth in the soil, depth of socketing into the rock-strata and the behaviour of the pile. Therefore, there is a need for a comprehensive field and lab-scale experimental study for the validation of the existing methods of analysis. So, in this paper, the lateral response of socketed pile has been discussed by conducting a series of experiments on instrumented model piles through variation of its depth of socketing up to 3D with an increasing order of $0.5D$ (D is diameter of pile) and increase in the (L_e/L) ratio, where L_e is depth of embedment and L is total length of pile with which the behaviour of the pile varies from short rigid to long flexible. Therefore, presenting a complete understanding of the behaviour of rock-socketed piles subjected to lateral loading. Nandhagopal and Muthukkumaran [24] studied the effect of rock-socketing on laterally loaded piles installed in the proximity of sloping ground and reported that the effect of socketing is most significant on the piles situated on the slope than the piles on the embankment.

Experimental program

Testing chamber

A test tank of size $2 \times 1 \times 1$ m (length \times width \times height) made of 5 mm thick sheet of mild steel was fabricated to facilitate lateral load on socketed model pile without any boundary effect as presented by Begum et al. [1], Begum and Muthukkumaran [2] and Muthukkumaran and Begum [23]. Calculations for fixing the dimensions of the tank were based on the Rankine's theory and zone of influence of the pile by knowing the depth of fixity z_f as suggested by Davisson and Robinson [6],

$$\text{Depth of point of fixity, } z_f = 1.8T \quad (1)$$

$$T = \sqrt[5]{\frac{EI}{\eta_h}} \quad (2)$$

η_h = coefficient of modulus of subgrade reaction. The value of coefficient of horizontal modulus of subgrade reaction ' η_h ' for sand (according to [30] is 2.5 MN/m^3 for loose sand. The minimum length of the test tank estimated for relative density of loose sand is 678 mm. Therefore, the tank dimensions selected are well clear of the boundary limitations. Figure 1 shows the isometric and photographical view of the test tank with installed model pile with a reaction frame of capacity 5 ton used to holding the actuator in position.

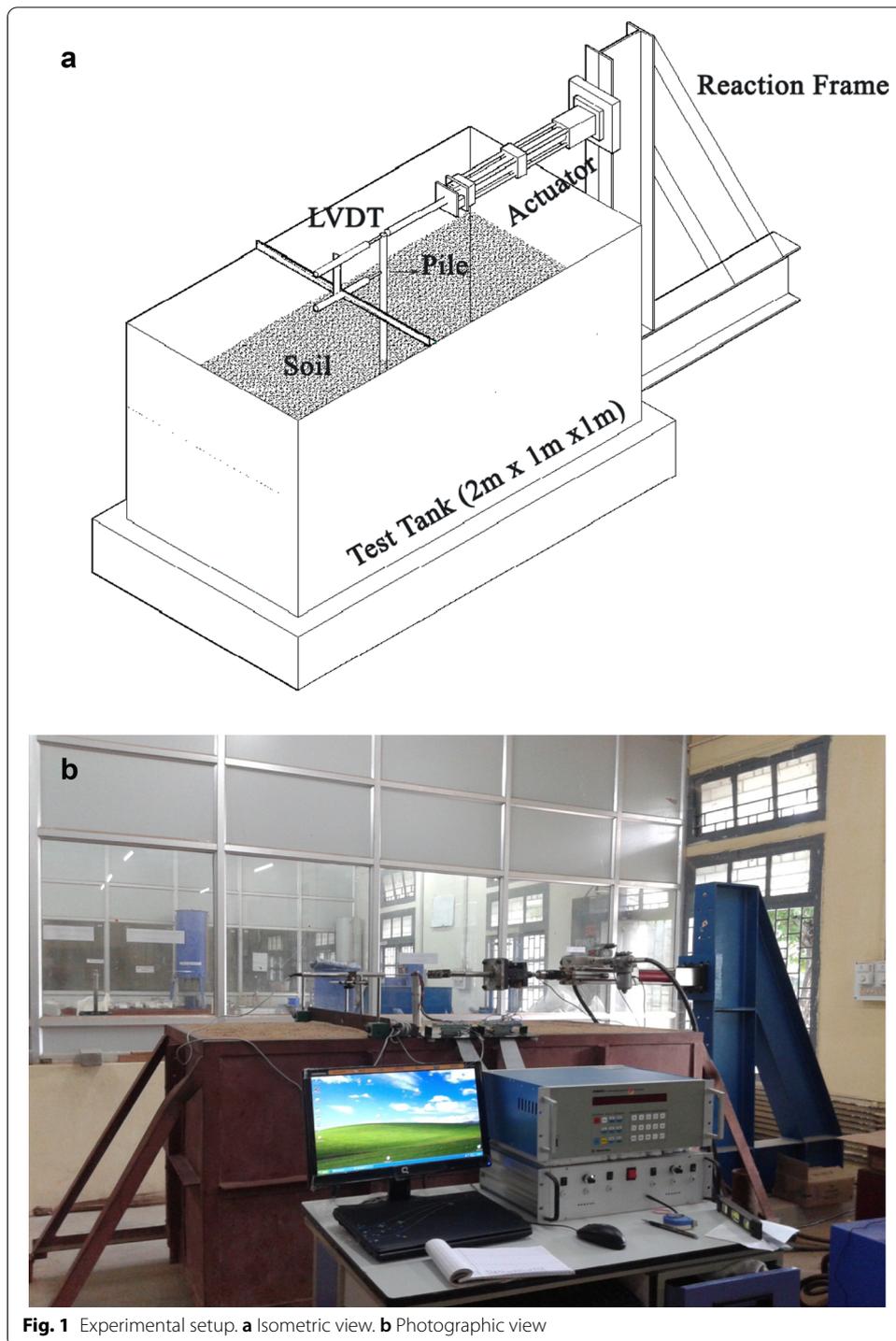
Soil sample description

The soil used for the experimental study was collected from River Cauvery, Trichy, India which is classified as poorly graded sand (SP) as per IS 1498-2002 [11]. The soil sample has an average particle (D_{50}) size of 0.43 mm with an effective diameter (D_{10}) of 0.2 mm. The gradation chart for the collected sand is shown in Fig. 2. The River sand has uniform silica sand, with a coefficient of uniformity $C_u = 2.5$ and coefficient of curvature $C_c = 1.16$ with subangular particles as per IS 2720 (Part-4)-2006 [13]. The maximum (ρ_{\max}) and minimum (ρ_{\min}) dry densities of sand were obtained as per IS 2720-(Part-14)-2002 [15] and found to be 19.1 kN/m^3 and 14.9 kN/m^3 respectively. The direct shear test was conducted as per IS 2720-(Part-13)-2002 [14] and the angle of internal friction (ϕ) found to be 34.6° . The specific gravity of soil sample was found to be 2.62 as per IS 2720-(Part-3/Sec-1)-2002 [12].

Throughout the entire experimental programme, the soil sample was filled in the tank with a constant relative density of $R_D = 30\%$ (loose state) using the sand raining technique adopted by Muthukkumaran and Begum [23] and Muthukkumaran [22]. The relative density test was conducted as per IS 2720-(Part-13) for calibrating the sand raining device. Figure 3 shows relative density variation with height of fall. In order to maintain the loose state relative density (relative density 30%) at the ground level, the height of fall of the sand raining device was maintained as 5.0 cm.

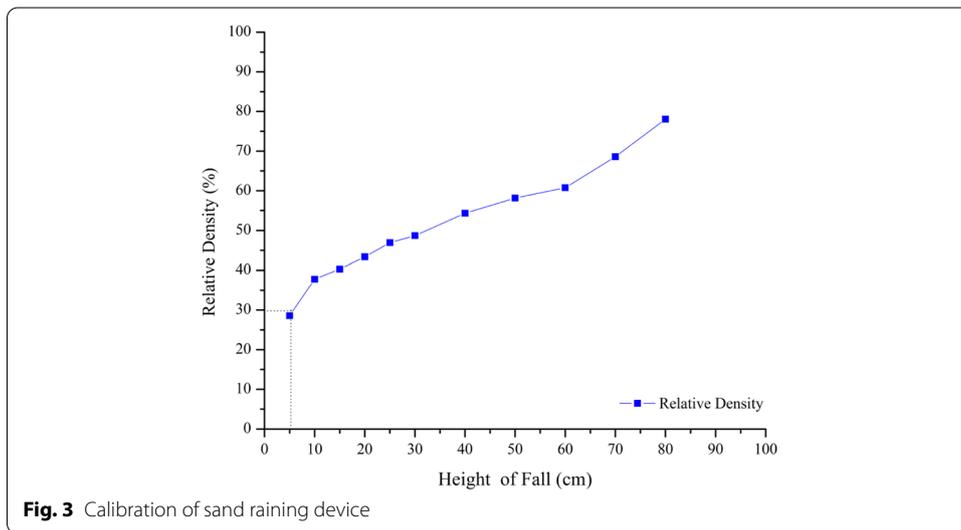
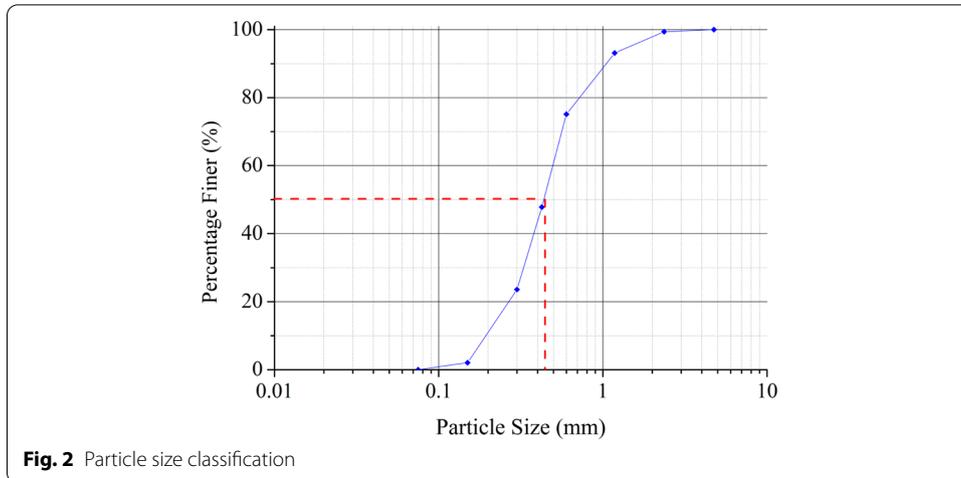
Model pile

Three model piles were chosen with different diameters of 25.4 mm, 38.1 mm and 50.8 mm with 3 mm thickness and 1200 mm length each. The model piles were made of hollow aluminium pipe of having Young's modulus of 70 GPa.



The scaling laws expressions for the flexural rigidity of the pile (EI), applied lateral load (F), loading eccentricity (L_e), modulus of subgrade reaction (η_h) and pile deflection (y) have been derived based on Buckingham Pi theorem and presented below.

$$(EI)_p = c_1^5 * c_2^1 * (EI)_m \quad (3)$$



$$F_p = c_1^3 * c_2^1 * F_m \tag{4}$$

$$\eta_{hp} = c_2^1 * \eta_{hm} \tag{5}$$

$$\left(\frac{L_e}{D}\right)_p = \left(\frac{L_e}{D}\right)_m \tag{6}$$

$$\left(\frac{L_f}{D}\right)_p = \left(\frac{L_f}{D}\right)_m \tag{7}$$

$$\left(\frac{L_s}{D}\right)_p = \left(\frac{L_s}{D}\right)_m \tag{8}$$

where, c_1 and c_2 are the scaling factors related to the pile diameter and unit weight of the soil such that $D_p = c_1 * D_m$ and $\gamma_p = c_2 * \gamma_m$. The unit weight does not vary between the test conditions and the field conditions and therefore, c_2 is unity. The suffixes ' p ' and ' m ' given to the variables corresponds to the prototype and model conditions respectively. Assuming a scale factor of 20, the model piles shall represent a range of prototype piles of diameter 500 mm to 1025 mm. The modelling of model tests was done considering D/d_{50} greater than 45 such that there is no significant grain-size effect [9] and [25].

Model pile installation

The model pile was installed as a pre-installed pile (like cast-in-situ pile) at a particular location before pouring the sand. The verticality of the pile was checked before filling the soil as well the verticality was ensured at each stage of sand filling. Temporary clamps were used for holding the pile in position and removed while the load was applied. The sand was filled to the desired level with density index of $R_D = 30\%$ throughout the experimental program with the help of a sand raining device. A geo-gauge device was used to ensure the density of sand at a regular interval of height in the test tank.

Depth of rock socketing

The depth of socketing was achieved by grouting a concrete layer around the model pile to the required depth. In order to achieve moderately weathered rock socketed behaviour, a concrete mix of M_{50} was used. The grouting of concrete was done carefully in order to achieve the homogeneity. The pile is socketed at the center of a concrete plug with equal length and breadth which was 600 mm. The thickness of the plug was provided as per the required depth of socketing which ranges between 0.5 to 3 times the pile diameter. The compressive strength and modulus of elasticity of the concrete were also estimated based on compression tests and found to be 50 N/mm^2 and $35,503.81 \text{ N/mm}^2$ respectively which lies within the range of moderately weathered rock conditions ($E_{rock} = 20,000$ to $40,000 \text{ N/mm}^2$).

Test program

Lateral load tests were conducted by a displacement controlled actuator of capacity 10kN. The load was applied at the pile head level. Linearly varying differential transducers (LVDT) of travel length 50 mm with accuracy of 0.01 mm were placed at pile head and at the ground level for measuring the magnitude of the pile lateral movement. The rate of load increment was maintained as 0.01 mm/sec and resistance to deformation of pile head was measured with the help of load cell attached to the actuator of accuracy 0.01 N. The load was applied until the measured ground level deflection was greater than 4 mm for all the cases as per IS 14593-2003 [16]. The reading from LVDT and load cell were recorded for every 3 s with the help of the computer controlled Data Acquisition System. The torsional rotation and vertical movement of the pile head was measured with the help of torque transducer, LVDT respectively and found to be negligible for all the cases.

A total of 84 set of experiments were carried out by varying the length of depth of embedment to total length of the pile (L_e/L) as 0.83, 0.67, 0.5 and 0.33, where the length of the pile was kept as constant and pile diameter changed. Similarly, the socketed depth

was increased at an equal interval of 0.5D (diameter of the pile). The tests were also done on non-socketed pile with different L_e/L ratios for better comparison.

Result and discussion

Classification of model piles

The ultimate lateral resistance of the pile mainly depends on pile response against the applied lateral load. The pile response can be classified [3] on the basis of the soil subgrade reaction and the flexural stiffness (EI) of the pile. Unsaturated cohesionless sand has been used in the present study, where soil modulus linearly varies with depth and minimum at the ground level. The piles were classified in accordance to IS 2911 (Part 1/ Sec 4)—2010 [17], where the piles are considered long (elastic) when $L \geq 4 T$ and short (rigid) when $L \leq 2 T$. Where, T = Stiffness factor was obtained using Eq. 2. The values of coefficient of subgrade reaction was taken as per Terzaghi [30], corresponding to sand in loose condition.

The behaviour of the pile in every case has been presented in Table 1. From the table, the pile having minimum free standing height of 200 mm (L_e -1000 mm) and diameter of 25.4 mm will be behaving as a long flexible pile. The pile of 38.1 mm diameter with depth of socketing greater than 1D having (L_e -600 mm) and pile of 25.4, 38.1 and 50.8 mm diameter pile with L_e -400 mm behave as a short rigid pile. The remaining model piles may be expected to behave as intermediate piles.

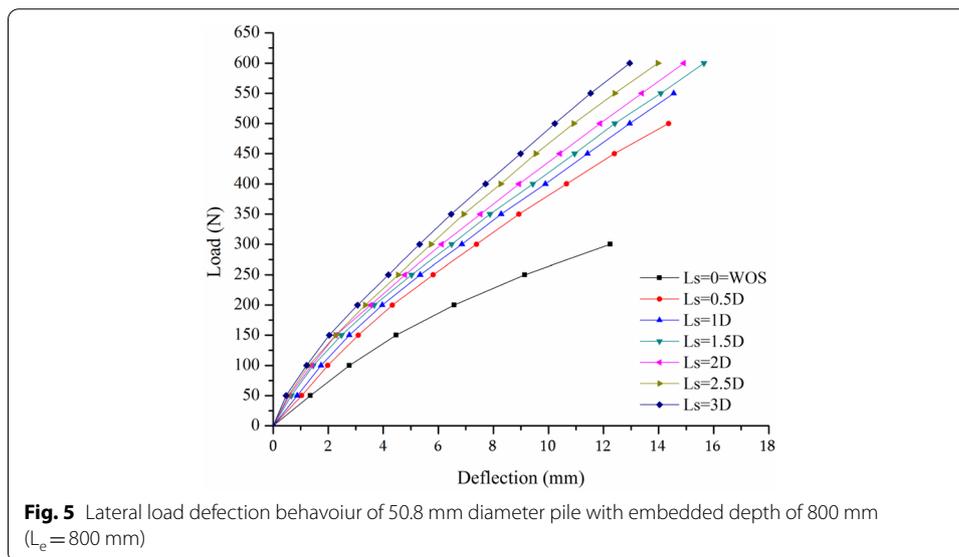
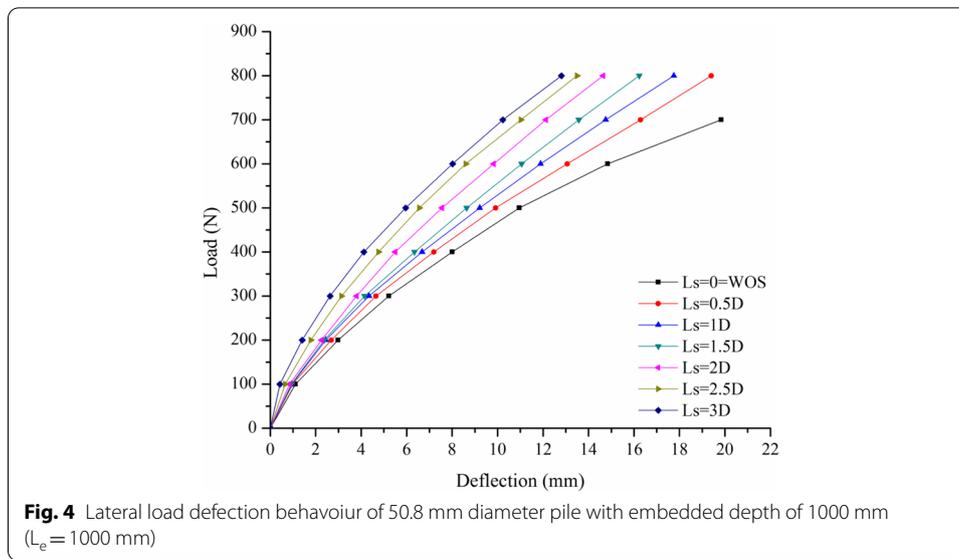
Lateral load deflection response

The lateral load capacity of the pile is estimated based on the deflection at the ground level. Therefore, the developed lateral deflection at the ground level vs. lateral load curves for 50.8 mm diameter pile with varying length of embedded pile in soil and varying socketed depths in rock (concrete) have been presented in Figs. 4, 5, 6, and 7. From the figures, it can be observed that the increase in depth of socketing into a hard stratum results in decreasing the pile head deflection and increase in the lateral load carrying capacity of pile all the piles. In case of $L_e = 1000$ mm as shown in Fig. 4, for an applied load of 50 N (at lower loading condition) ground level deflection decreased by 12%, 14%, 16%, 23%, 40% and 62% for increasing depth of socketing of 0.5D, 1D, 1.5D, 2D, 2.5D and 3D respectively, compared to a pile without socketing (WoS). For L_e 600 mm (Fig. 6), lateral deflection is reduced by 118%, 145%, 166%,

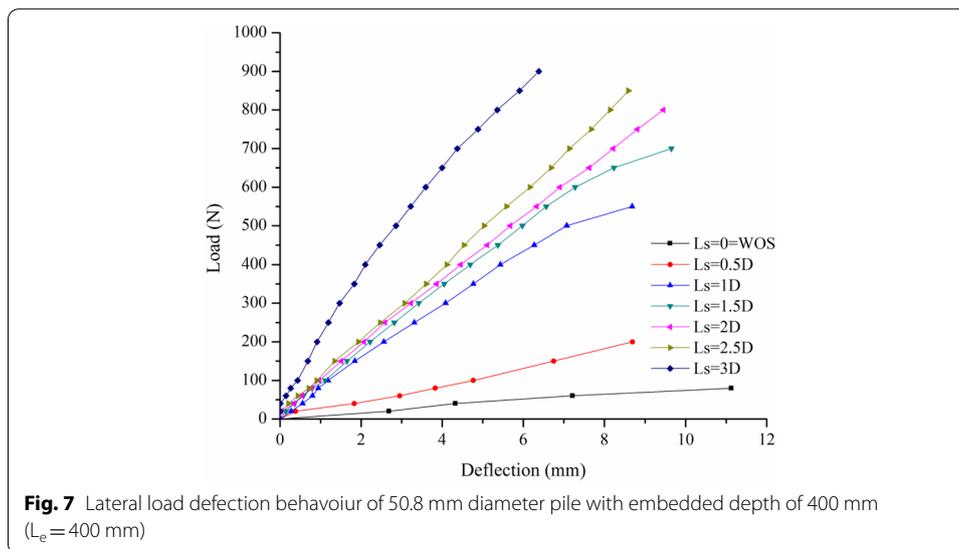
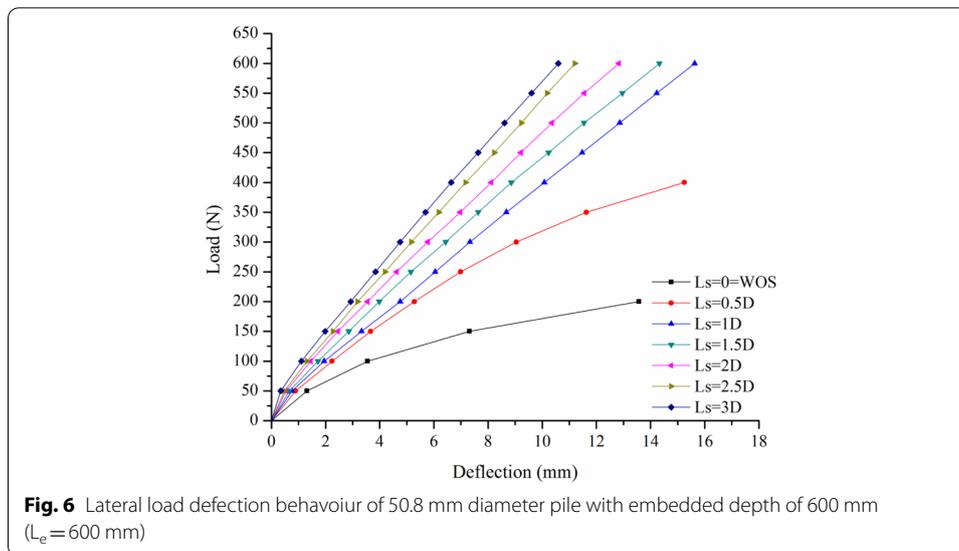
Table 1 Experimental model pile behaviour

Pile diameter D (mm)	25.4	38.1	50.8	25.4	38.1	50.8	25.4	38.1	50.8	25.4	38.1	50.8
Free Standing Height L_e (mm)	200			400			600			800		
WoS	LP	IP	SP	SP	SP	SP						
0.5D	LP	IP	SP	SP	SP	SP						
1D	LP	IP	IP	IP	IP	IP	IP	SP	SP	SP	SP	SP
1.5D	LP	IP	IP	IP	IP	IP	IP	SP	SP	SP	SP	SP
2D	LP	IP	IP	IP	IP	IP	IP	SP	SP	SP	SP	SP
2.5D	LP	IP	IP	IP	IP	IP	IP	SP	SP	SP	SP	SP
3D	LP	IP	IP	IP	IP	IP	IP	SP	SP	SP	SP	SP

LP Long flexible pile, IP intermediate pile, SP short rigid pile, D diameter of pile, WoS without Socketing



190%, 203% and 221% for increasing depths of socketing of 0.5D, 1D, 1.5D, 2D, 2.5D and 3D respectively. For L_e 400 mm (Fig. 7), lateral deflection is reduced by 660%, 921%, 934%, 936%, 942.06% and 982% for increasing depths of socketing of 0.5D, 1D, 1.5D, 2D, 2.5D and 3D respectively. It can be observed for pile diameter 50.8 mm having EI of 9.042 kN/m^2 , the effect of depth of socketing has a greater effect from 0.5D onwards on pile head deflection. This is due to the increase in stiffness of the pile and short rigid pile behaviour. It can also be observed from the values that the depth of socketing in hard stratum has insignificant effect on the pile head deflection when the pile has maximum depth of pile embedment of 1000 mm ($L_e = 1000$ mm) whereas, the lateral deflection is moderately significant for lesser depth of embedment ($L_e = 800, 600$ and 400 mm) in sand. A similar trend was observed in 25.4 mm and 38.1 mm



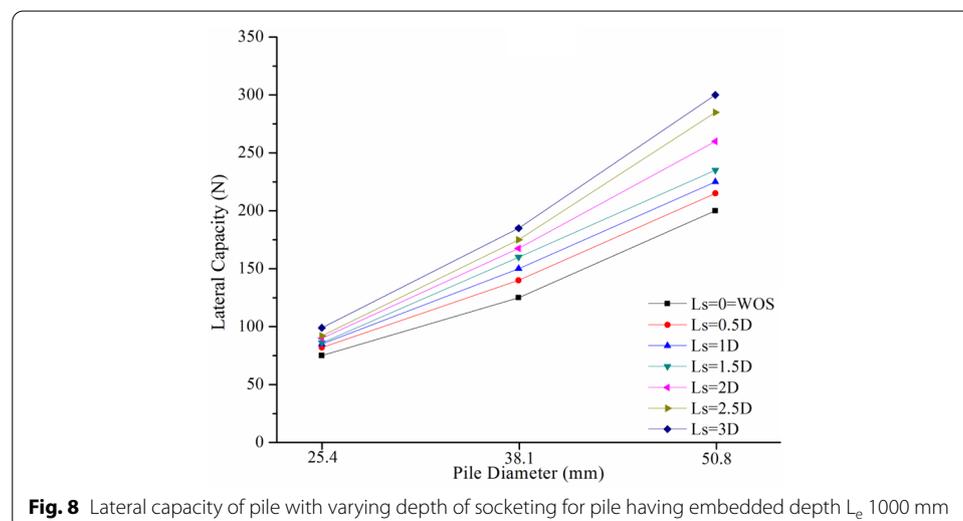
diameter piles. But, in case of 25.4 mm diameter pile with $EI = 0.944 \text{ kN/m}^2$ flexural rigidity and L_e 1000 mm above the ground level. In this case, for an applied load of 50 N the ground level deflection decreased by 23%, 29%, 33%, 36% and 52% for increased depth of socketing of 0.5D, 1D, 1.5D, 2D, 2.5D and 3D respectively, when compared to a pile without socketing condition (WoS) which is greater reduction that compared to the 50.8 mm diameter pile. This can be attributed to the long flexible behaviour of pile and greater passive resistance offered by the overlying soil. Therefore, in long flexible piles, the effect of rock socketing is almost negligible in the lateral response and hence socketing may not be needed.

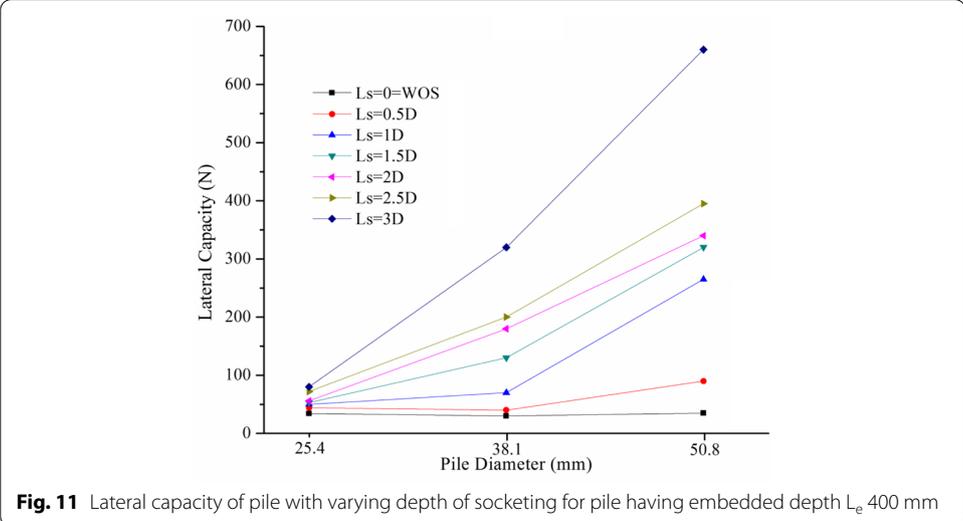
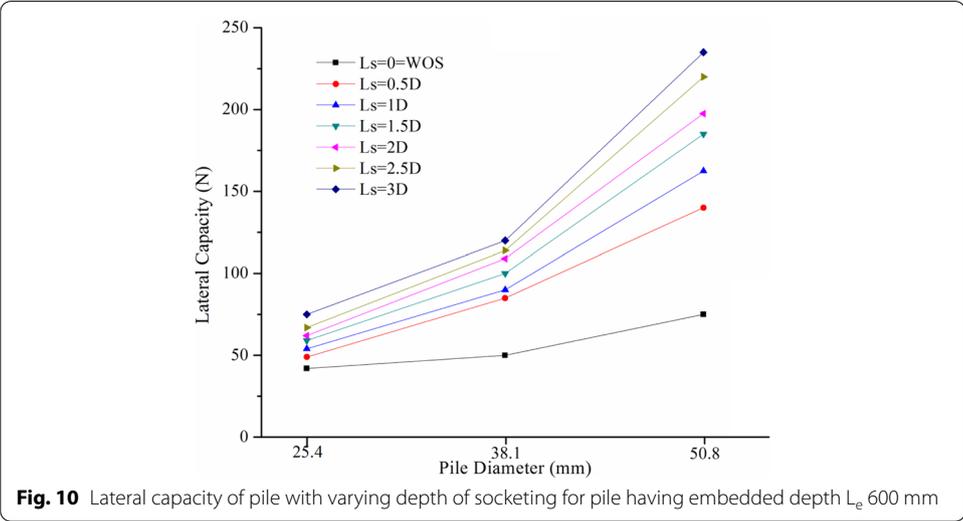
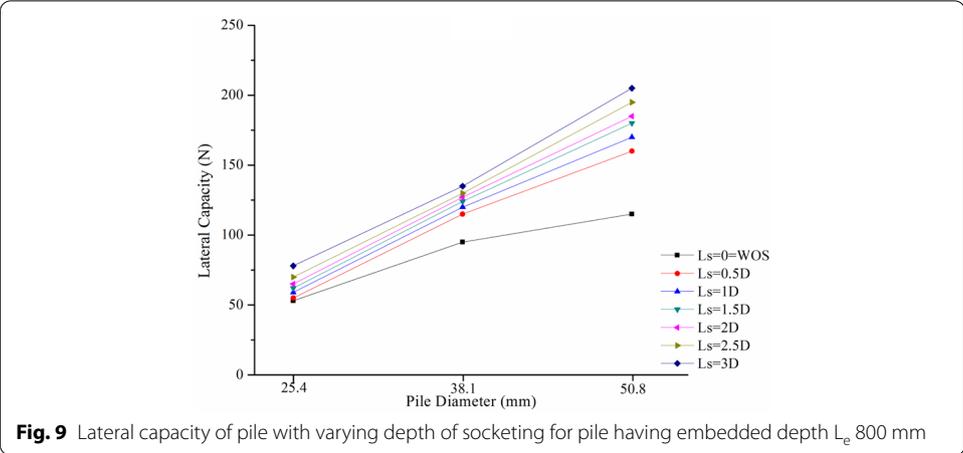
In the case of 38.1 mm diameter pile with EI of 3.592 kN/m^2 of which most cases fall under intermediate pile behaviour, the reduction in lateral pile head deflection due

to the effect of depth of socketing was observed to be less significant up to a depth of socketing of 1D and greater effect for 1.5D to 3D depth of socketing at all embedment depths. To quantify, L_e 1000 mm above ground level. In this case, for an applied load of 50 N, ground level deflection is reduced by 18%, 30%, 46%, 50%, 56% and 72% for increasing depths of socketing of 0.5D, 1D, 1.5D, 2D, 2.5D and 3D respectively, compared to a pile without socketing (WoS). For L_e 400 mm, the ground level lateral deflection is reduced by 264%, 480%, 559%, 595%, 621% and 650% for increasing depths of socketing of 0.5D, 1D, 1.5D, 2D, 2.5D and 3D respectively.

Lateral capacity of socketed pile

Estimation of the safe lateral load for socketed pile was estimated as per IS 14593–2003 [16]. As per code recommendation, the safe load for socketed pile is the minimum of the load corresponding to 4 mm deflection or 50% final load at which the total displacement of 8 mm. Figures 8, 9, 10, and 11 show the measured safe load for all three pile diameters with increase in depth of socketing (L_s) corresponding to 4 mm deflection at ground level. From the results presented in these figures, it is very clearly seen that, the depth of embedment play a major role in the pile capacity irrespective of the depth of socketing. That is, the influence of depth of socketing can be observed to have an insignificant effect on lateral capacity of small diameter piles ($D=25.4$ mm) whereas the depth of socketing is significantly increases lateral pile capacity in large diameter piles ($D=38.1$ & 50.8 mm) in cases of lower depth of embedment. This effect can be clearly observed in Fig. 11, where depth of embedment is minimum ($L_e=400$ mm). To quantify, at L_e 400 mm, the lateral capacity of the 25.4 mm pile increases only by 1.29, 1.47, 1.56, 1.65, 2.12, and 2.35 times lateral capacity times the capacity of without socketed pile with increase in depth of socketing from 0.5D to 3D. Whereas, the 38.1 mm pile improves by 1.33, 2.33, 4.33, 6.00, 6.67 and 10.67 times the capacity of without socketed pile and the lateral capacity of 50.8 mm diameter pile increases by 2.57, 7.57, 9.14, 9.71, 11.29 and 18.86 times the capacity of without socketed pile for 0.5D, 1D, 1.5D, 2D, 2.5D, and 3D depth of socketing cases respectively. From this observation, it is very clear that the socketing depth is having a significant improvement of





lateral load capacity on short piles. This is may be due the enhanced relative stiffness of the soil-pile-rock system in short piles.

On the other hand, from Fig. 8, where the embedded length of the pile is maximum at $L_e = 1000$ mm, the effect of socketing does not appear to be very significant in most cases. Numerically, at maximum embedded depth of L_e 1000 mm, the lateral load capacity of 25.4 mm diameter pile increases linearly with increase in depth of socketing and it increases by 1.09, 1.13, 1.15, 1.20, 1.23 and 1.32 times the load carrying capacity of the without socketed pile. Whereas, the load carrying capacity of the 38.1 mm diameter pile increases by 1.12, 1.20, 1.28, 1.34, 1.40 and 1.48 times the load carrying capacity of the without socketed pile. Also, under identical conditions the load carrying capacity of the 50.8 mm diameter pile improves by 1.08, 1.13, 1.18, 1.30, 1.43 and 1.50 times. This can again be attributed to the long flexible behaviour of pile and greater passive resistance offered by the overlying soil.

The magnitude of lateral capacity gradually increases with increase in the depth of socketing and pile diameter for all L_e/L ratios. However, in greater L_e/L (0.83 & 0.67) piles, the depth of socketing made slight difference in lateral capacity as shown in Figs. 8 and 9. Figure 10 shows an exponential increase in the load capacity with increase in depth of socketing for L_e/L of 0.5, which can be attributed to the resistance offered by hard stratum (socketed depth). For the case L_e/L of 0.33, where the embedded depth in soil is minimum ($L_e=400$ mm) as shown in Fig. 11, the influence of subgrade reaction of hard stratum is maximum resulting in load carrying capacity increasing dramatically with increase in depth of socketing.

Expression for lateral load capacity of socketed pile

Although, the improvements in lateral capacity were comparatively insignificant in cases of piles with greater L_e/L ratio, the experimental results showed the effect of socketing depth (L_s) had an influence on lateral load capacity of all three diameter piles in all cases. For a minimum embedment depth of pile in soil ($L_e=400$ mm) and maximum depth of socket ($L_s=3D$), the pile capacity dramatically increased 18.86 times the capacity of pile without socketing.

For a pile having $L_e = 600$ and $L_e = 800$ mm, the lateral capacity increases with increase in depth of socketing linearly with an incremental order of 0.2 times the capacity of pile without socketing, except in the case of a pile having a diameter 50.8 mm and depth of socketing 3D. Based on the experimental results, empirical equations were proposed by multi regression analysis for estimating the allowable lateral load (P_a) on socketed. The experimentally obtained pile capacity for each case of the test was taken as dependent variable and the ratio of depth of embedment of pile in soil to the diameter of pile (L_e/D), the ratio of the length of free standing height to the diameter of pile (L_f/D) and ratio of length of socket depth to diameter of pile (L_s/D) were considered as independent variable for the multi regression analysis. From the analysis, it is observed that the pile capacity bi-linearly varying with respect to (L_e/D), (L_f/D) and (L_s/D). Therefore, two sets of equations are proposed with respect to L_e/L ratio.

$$P_a = 3.95(L_e/D) + 3.78(L_f/D) - 119.43(L_s/D) \quad \text{For } L_e/L > 0.3 \quad (9)$$

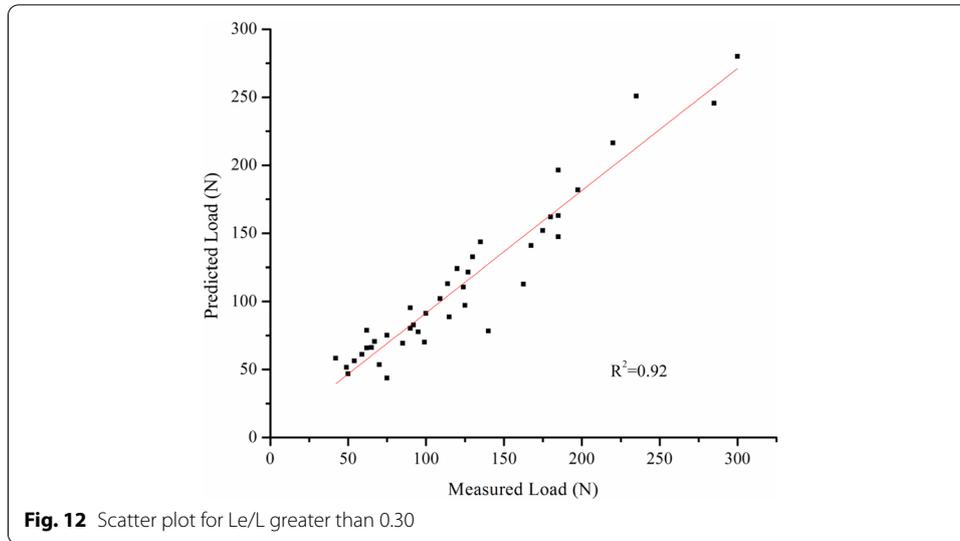


Fig. 12 Scatter plot for L_e/L greater than 0.30

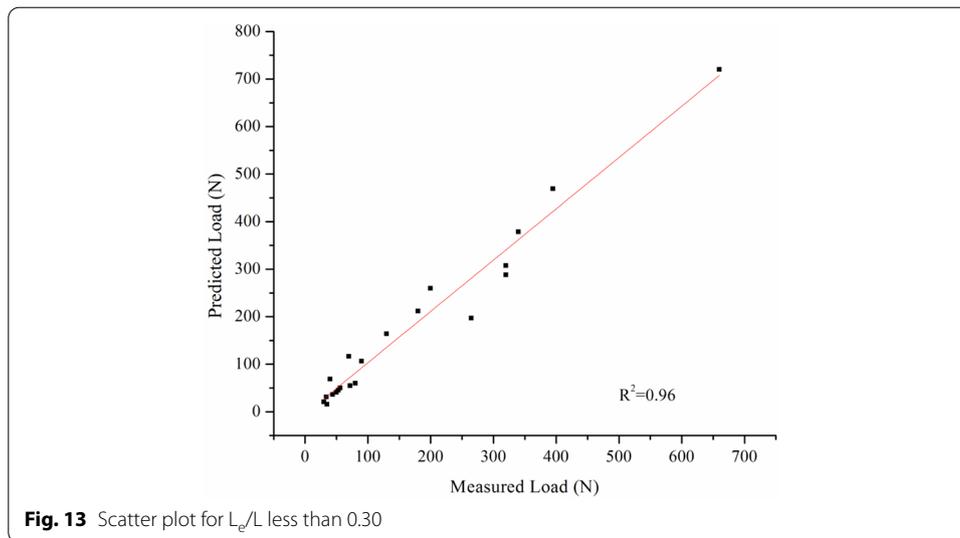


Fig. 13 Scatter plot for L_e/L less than 0.30

$$P_a = 1.98(L_e/D) + 6.77(L_f/D) - 162.45(L_s/D) \quad \text{For } L_e/L < 0.3 \quad (10)$$

Scatter plot for actual measured lateral capacity and predicted lateral capacity using Eqs. (9) and (10) are plotted and presented for L_e/L greater than 0.30 and less than 0.30 in Figs. 12 and 13 respectively. The regression coefficient (R^2) was obtained as 0.92 and 0.966 for Eqs. (9) and (10) respectively, which means that the predicted values of lateral pile capacity of socketed pile are very well agree with experimental values of socketed piles. It should be noted that the above equations were developed based the experimental test results (1-g) on model pile made of aluminium tube under low confining stress conditions in unsaturated cohesionless sand as top layer and concrete as bottom rock layer. Therefore, the application of the above equations is limited to the selected parameters.

Conclusions

The lateral behaviour of socketed pile has been investigated in this paper by conducting 84 set of 1 g experimental studies on instrumented model pile having three different diameters of 25.4 mm, 38.1 and 50.8 mm with varying depth of socketing from 0.5D to 3D with an increasing the order of 0.5D. From the experimental studies the following conclusions are drawn.

1. The influence of the depth of socketing is significant only for L_s greater than 2.0D in the case of L_e/L ratio greater than 0.67. However, the influence of the depth of socketing L_s greater than 2.0D is dramatically increases the pile capacity in the case of L_e/L ratio less than 0.67. From this observation, it is concluded that the depth of rock socketing is insignificant for the L_e/L ratio greater than 0.67 as for as lateral load capacity concern.
2. The pile diameters play a major role along with socketed depth in the lateral capacity of socketed piles. The lateral pile capacity is increased by 18 times when the pile is socketed with 3D in larger diameter (50.8 mm) pile for L_e/L ratio of 0.33. From this observation, it is concluded that, the larger diameter piles (mono-piles) have greater lateral capacity under proper depth of socketing.
3. Based on the experimental results, empirical equations were developed to determine the allowable lateral capacity of the pile with respect to depth of rock socketing. These equations can be used to estimate the socketed pile lateral capacity with parameter limitations.

List of symbols

ϕ : Angle of internal friction; C_c : Co-efficient of Curvature; C_u : Co-efficient of Uniformity; D: Diameter of the pile; D_{10} : Percentage of particle size finer than 10%; D_{50} : Percentage of particle size finer than 50%; DAS: Data acquisition system; G_s : Specific Gravity; EI: Flexural stiffness of pile; L: Length of pile; L_e : Embedment length of pile in soil and hard stratum; L_f : Free standing length of pile above the ground level; L_s : Socketed length of pile in hard stratum; LVDT: Linearly varying differential transducer; P_a : Allowable lateral load; R^2 : Regression Co-efficient; R_D : Relative Density Index; WoS: Without socketing.

Authors' contributions

ARP Carried out the experimental study, experimental data analysis and prepared the draft manuscript. KM developed the technical concept for the experimental study, corrected the experimental data and reviewed and finalized the manuscript. Both the authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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