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Analysis of Laterally Loaded Single Pile in Cohesionless Soil Considering Nonlinear Soil-Structure Interaction Effects

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Abstract. Beam on nonlinear Winkler foundation (BNWF) is a simplified and most widely used model for analysis of nonlinear soil-structure interaction problem. In this study a numerical model is developed for laterally loaded single pile using open-source finite element-based code OpenSees. Pile and soil are simulated by displacement-based beam element and nonlinear spring element respectively. p-y curves based on API procedures are used for simulating nonlinear behaviour of soil. Pile tip is considered as floating base constraint. Three types of cohesionless soil based on relative density are considered: loose, medium and dense sand. The present analysis is validated using the theoretical solution of Reese and Matlock (1956). The effects of relative density of cohesionless soil, slenderness ratio(L/D) of pile and fixity of pile head on pile and soil responses are investigated. The results show that the lateral displacement of pile decreases drastically with the increase of relative density of soil. The lateral displacement of long pile for loose and dense sand is reduced by 69.75% and 73.90% respectively when the pile head fixity changes from free to fixed head condition. Also, it is overserved that the maximum bending moment of free head and fixed head long pile is decreased by 41.10% and 45.60% respectively when the soil type changes from loose to dense. The behaviour of pile as short rigid or long flexible, response of pile and soil are highly influenced by slenderness ratio of pile. Pile of L/D less than 10 behaves like short rigid pile and more than 10 behaves like long pile. The negative tip displacement is more for short pile with compared to long pile.

Keywords: Single pile; BNWF; Finite element; pile head fixity; Slenderness ratio

1 Introduction

Foundation is a substructure built below the superstructure to transfer the structural loads safely to the underlying soil. Piles are slender member primarily used to transfer vertical load from superstructure to deep soil strata or rock**.** Pile foundations are also required to carry both vertical and lateral loads in high rise buildings, bridges, chimney, transmission towers, port and harbour structures. The major causes of lateral loads are wind action, lateral earth pressure, impact load, water pressure, seismic forces. Ultimate lateral resistance of soil and maximum allowable lateral displacement of pile are the two principal criteria for design of laterally loaded pile (LLP) foundation. The ultimate lateral resistance of a single pile depends on both geotechnical properties of soil and structural properties of pile. The pattern of failure of short and long piles are also different. The failure of short pile is due to rigid body translation or rotation whereas that of long pile is by forming one or more plastic hinges. Hence, slenderness ratio of pile has a profound influence on lateral response of single pile.

Lateral response of single pile has been analysed by several researchers in the past using analytical, numerical and experimental methods [1-11]. The response of LLP in layered soil has been evaluated considering constant but different modulus of subgrade reaction for each layer [12]. Liyanapathirana and Poulos [13] proposed pseudo-static approach for analysis of LLP. The effects of vertical load on LLP foundation has also been evaluated by several researchers [14-16]. The solution of LLP is complex problem and involves nonlinear soil-structure interaction (SSI) effects. The exact solution of LLP foundation is not well established unlike vertically loaded piles (VLP). Only approximate solutions based on theoretical analysis are presented in Indian standard code of pile foundations IS-2911 [17]. The effects of SSI are neglected in conventional design practice assuming fixed base condition to avoid complexity of the problem. However, this assumption valid for low rise structures resting on stiff soil. The consideration of SSI becomes compulsory for laterally loaded high rise structures resting on soft soil. The flexibility of the supporting soil medium affects the time period and damping properties of the structure. So, the seismic response of structure may not be accurate by neglecting or oversimplifying the SSI effects. The effects of nonlinear SSI on free and fixed head single pile under lateral load in cohesionless soil is investigated in the current study using Beam on nonlinear Winkler foundation (BNWF) model. The simplified BNWF model is capable to incorporate nonlinear SSI effects accurately with less computational operation. The effects of various soil types on pile and soil response are investigated for single pile considering nonlinear SSI effects. The effects of slenderness ratio (L/D) and pile head fixity condition are also studied for loose sand.

2 Model Description

A 3D soil-pile model has been built using open source finite element-based code, OpenSees [18]. BNWF model is used to model the interaction between pile and soil as shown in Fig. 1. Pile and soil are simulated by displacement-based beam element and nonlinear spring element respectively. p-y curves based on API procedures [19] are used for simulating nonlinear behaviour of soil. The model is developed with three different sets of nodes: fixed spring nodes, slave spring nodes and pile nodes.

The finite element mesh is generated using element length of 0.5 m. The three-dimensional spring nodes having three translational degrees of freedom are generated. Zero-length elements are used to define soil springs using fixed and slave-nodes. Distinct uniaxial material objects are used in the lateral and vertical directions. The p-y springs oriented in lateral direction represent lateral resistance of soil-pile interface. On the other hand, vertically-oriented t-z and Q-z springs represent skin friction along pile length and end bearing at pile base, respectively. The p-y, t-z and Q-z springs are defined using the PySimple1, TzSimple1 and QzSimple1 uniaxial materials, respectively. The detail backbone equations and parameters of these springs are presented by Boulanger et al. [20] and Boulanger [21]. The three-dimensional pile nodes are created with six degrees of freedom. Both translational and rotational degrees of freedom of pile nodes are considered. Orientation of the pile is done by specifying a linear coordinate transformation object. The topmost pile head node is simulated as free head condition to apply lateral load. The pile nodes are connected with slave nodes of soil springs using equal degree of freedom command. Here the pile nodes are considered as master nodes. Both the nodes share equal degrees of freedom in lateral and vertical direction. Elastic behaviour of pile is considered using elastic section object.

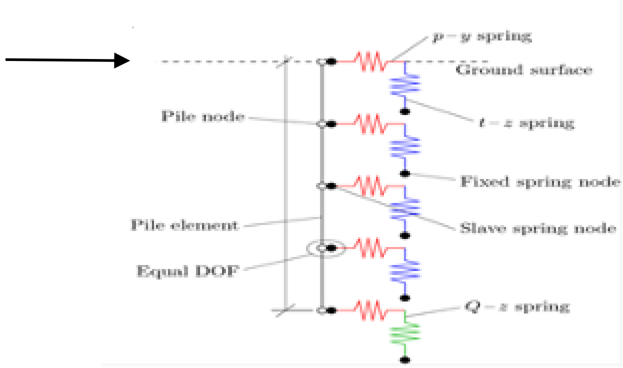


Fig. 1. BNWF modelling approach adopted for soil-pile interaction [18]

3 Validation of the Present Numerical Model

The reliability of the present finite element based numerical model is verified by comparing results with the theoretical solution of Reese and Matlock [22]. A laterally loaded single pile of length 10 m and diameter 0.5 m resting in loose sand is analysed using present model. The modulus of subgrade reaction is taken as 6800 kN/m3 [1]. Lateral load of magnitude 150 kN is applied at pile top. Figs. 2(a) and (b) present the comparison of lateral displacement and bending moment profile of pile using the present model and theoretical solution [22]. The present results are matching well with the theoretical solutions available in the literature. The slight deviation in results may be equitable due to different analysis methodology and soil model which are considered based on soil descriptions. Hence, the BNWF model implemented in OpenSees can be efficiently used for lateral response of pile foundation.

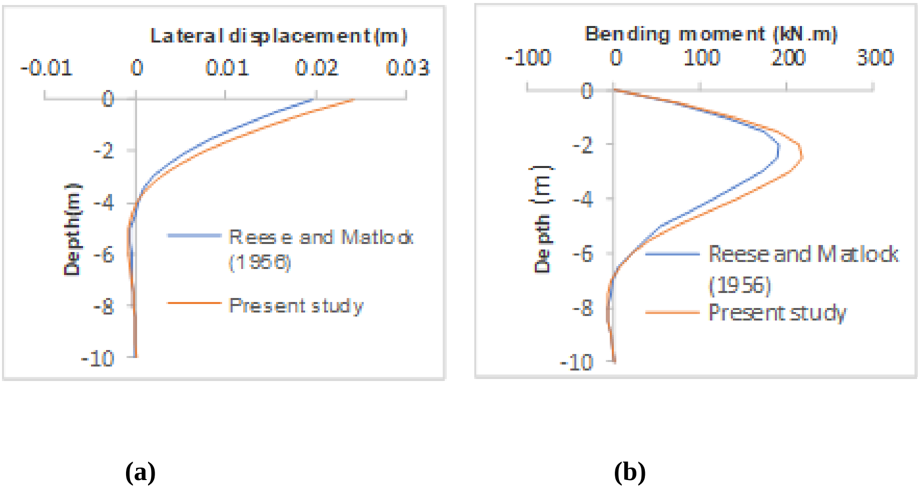


Fig. 2. Comparison of **a** lateral displacement and **b** bending moment response of pile obtained from present study with Reese and Matlock [22].

4 Results and Discussions

The behaviour of LLP foundation depends on a number of parameters. The effects of various soil types on pile and soil response are investigated using present model for single pile. The effects of slenderness ratio (L/D) of pile and pile head fixity are also studied. The length of pile is varied from 5.0 m to 15.0 m keeping diameter constant (0.5 m) for parametric study. Tables 1 and 2 summarises the properties of pile and soil used in the study respectively. The properties of pile and soil are taken from IS 456-2000 [23] and Das, BM [24] respectively. Single layer cohesionless soil is considered and the ground water table is considered well below the tip of the pile. Pile head is located at ground surface. Lateral load of 150 kN is applied linearly from 0 kN to 150 kN over a 10 sec at topmost pile node using plain pattern with elective time-series parameters. The load-controlled integrator is used to conduct the analysis.

Table 1. Pile parameters considered in the present study [23]

Particulars	Values
Length of pile (L)	15 m
Diameter of pile (D)	0.5 m
Lateral load (P)	150 kN
Grade of concrete	M30
Young's Modulus of Pile (Ep)	27400 MPa
Poisson's ratio of pile (μ)	0.2
Moment of inertia of pile (Ip)	0.003066 m4

Table 2. Soil parameters considered in the present study [24]

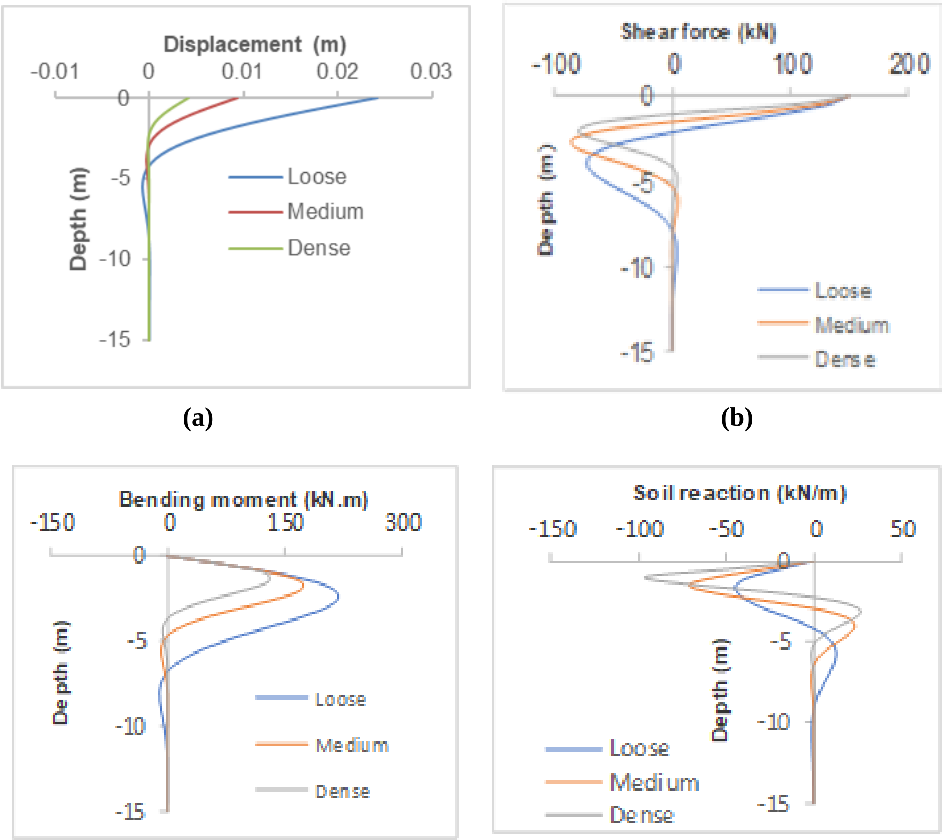
Soil type	Unit weight, γ (kN/m^3)	Young's Modulus,Es(MPa)	Poisson's ratio,μs	Friction angle, ϕ (°)
Loose sand	17	18	0.25	29
Medium sand	19	25	0.30	33
Dense sand	21	50	0.35	40

4.1 Influence of Soil type on pile and soil response

Static analysis for 15.0 m long pile (L/D=30) has been performed for loose, medium and dense soil types and the results are presented. Variation of lateral displacement profile of pile is presented in Fig. 3(a) for various soil types**.** It is observed that the maximum lateral displacements at free end for loose, medium and dense sand under same lateral load of 150 kN are 24.12, 9.33 and 4.22 mm respectively**.** Maximum lateral displacement is reduced by 82.50% when the soil type changes from loose to dense sand. So, the significant reduction of lateral displacement of pile is observed with the increase of stiffness of soil.

The variation of shear force and bending moment of the pile along depth are shown in Figs. 3(b) and 3(c) respectively. The peak value of shear force obtained is 150 kN at free head of the pile**.** The depths correspond to point of inflection are 2.5 m, 1.5 m, 1.5 m for loose, medium and dense sand respectively. The maximum values of bending moment are also affected by the stiffness of soil. The maximum bending moments are 218.18 kN-m, 170.33 kN-m and 128.58 kN-m for loose, medium and dense sand respectively. The depth correspond to peak bending moment is dependent on soil type. The peak value of bending moment of pile is reduced by 41.10% when the soil type changes from loose to dense sand. The depth of point of contraflexure from ground surface decreases with the increase of relative density of soil.

Fig. 3(d) presents the soil reaction profile for various soil types. The response is negative from the ground surface to about 4.5 m, 3.0 m and 2.5 m depth, then transitions to positive until about 9.0 m 6.0 m and 5.0 m depth, for loose, medium and dense sand, has a second smaller negative section, and then is nearly zero near the tip of the pile. The peak value of soil reaction obtained for loose, medium and dense sand are 44.12, 70.87 and 95.98 kN/m respectively. Also, the soil reaction of dense sand is 35.40% more than loose sand under same lateral load.



(c) **(d)**

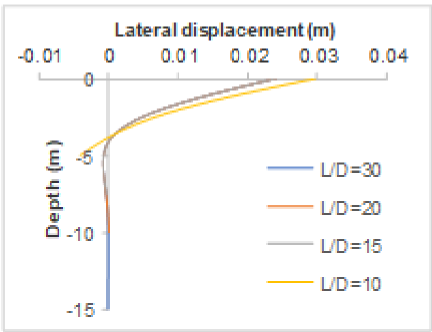
Fig. 3. Profile of **a** lateral displacement **b** shear force **c** bending moment of pile and **d** soil reaction response for various soil types.

4.2 Influence of pile slenderness ratio (l/d) on pile and soil response

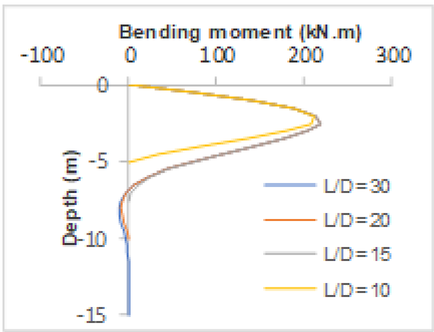
The behaviour of pile as short rigid or long flexible, response of pile and soil are highly influenced by L/D ratio of pile. Fig. 4(a) shows the impact of L/D on lateral displacement of pile in loose sand. The pile having L/D ratio 10 behaves like short rigid pile and tends to rotate with respect to point of inflection. The peak opposite displacement appeared at the bottom of short pile as shown in Fig. 4(a). The Piles having L/D ratio 15, 20 and 30 behaves like long flexible piles and the maximum negative displacement occurred in between inflection point and the base of pile. Also, the negative tip displacement is more for short pile with compared to long pile.

It is observed that the maximum bending moment are 211.55 kN-m for L/D ratio 10 and 218.18 kN-m for L/D ratio more than 10 in loose sand. Also, the maximum bending moment of pile decreases along length for L/D ratio 10 and 15. However, the negative bending moment occurs near the point of contraflexure and finally becomes zero at base of pile for L/D ratio 20 and 30 as shown in Fig. 4(b).

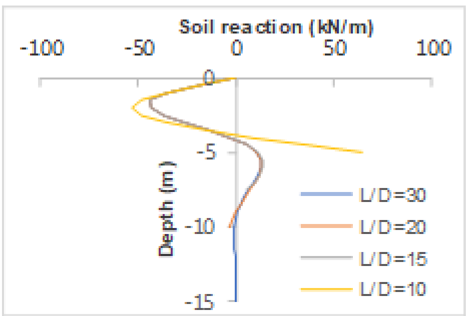
The soil reaction profile for various L/D ratio of pile in loose sand are presented in Fig. 4(c). The soil reaction is 46.80% more for short pile (L/D=10) than long piles (L/D more than 10) resting in loose sand. Also, soil reaction for the pile having L/D ratio 10 transitions to positive and becomes maximum at the pile tip. When L/D ratio exceeding 10 the reaction changes to positive and has a second smaller negative and tends to zero near the base of pile.



(a)



(b)

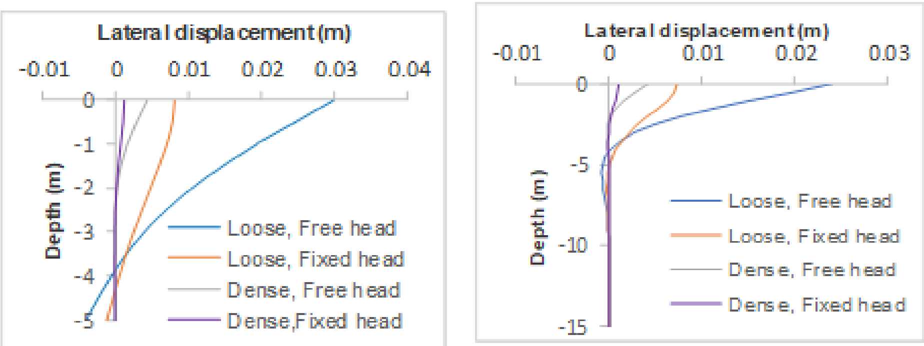


(c)

Fig. 4. Profile of **a** lateral displacement **b** bending moment of pile and **c** soil reaction response in loose sand for various pile slenderness ratio.

4.3 Influence of pile head fixity condition on pile and soil response

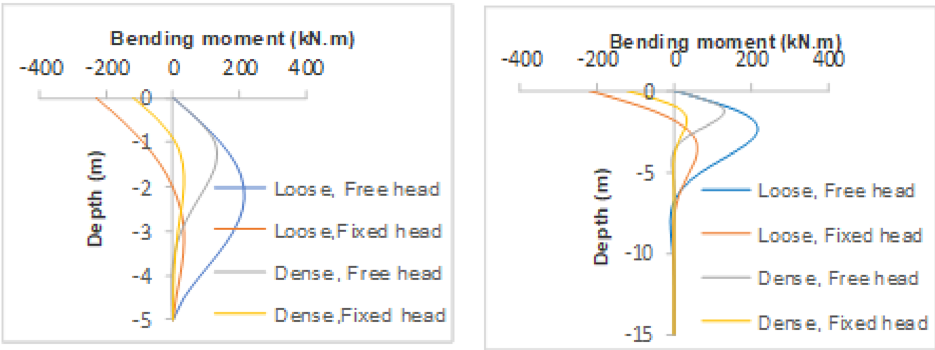
The effects of pile head fixity on lateral displacement response of short and long pile for loose and dense sand are presented in Fig. 5(a) and (b) respectively. The rigid behaviour showing rigid body rotation is noticed for short free and fixed head pile (L/D=10) in loose sand. But, in dense sand the flexible type behaviour was observed for same pile for both free and fixed head condition. However, the behaviour of long pile (L/D=30) is always flexible type for all types of soils and pile head fixity condition as shown in Fig. 5(b). Also, it is overserved that the lateral displacement of pile decreases significantly when the pile head fixity changes from free head to fixed head condition. The lateral displacement of long pile (L/D=30) for loose and dense sand is decreased by 69.75% and 73.90% respectively when the pile head fixity changes from free to fixed head condition.



(a) (b)

Fig. 5. Lateral displacement profile for **a** short pile (L/D=10) **b** long pile (L/D=30)

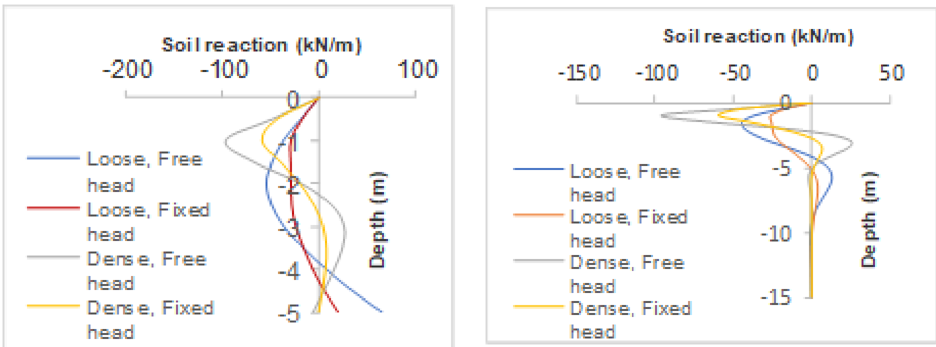
The bending moment profiles of short and long pile for different pile head condition and soil type are presented in Fig. 6(a) and (b) respectively. The pile head fixity condition and slenderness ratio have profound influence on bending moment profile. The depth corresponds to maximum bending moment are also different for free and fixed head pile. The maximum bending moment of free head and fixed head long pile is reduced by 41.10% and 45.60% respectively for changes of relative density of soil from loose to dense.



(a) **(b)**

Fig. 6. Bending moment profile for **a** short pile (L/D=10) **b** long pile (L/D=30)

The soil response is also dependent on pile head fixity condition for both short and long pile. Figs. 7(a) and (b) illustrate the soil reaction profile for short and long pile embedded in loose and dense sand. The pattern of soil reaction of short free and fixed head pile in loose sand is completely different with that of long pile.



(a) **(b)**

Fig. 7. Soil response profile for **a** short pile (L/D=10) **b** long pile (L/D=30)

5 Conclusions

A three-dimensional finite element BNWF model has been developed using the open-source software platform OpenSees to study the static response of single pile in cohesionless soil. The key conclusions from the results of present study are as follows:

1. The relative density of soil has profound influence on pile response. The maximum bending moment of free head and fixed head long pile is reduced by 41.10% and 45.60% respectively for changes of relative density from loose to dense.

2. The depth of point of contraflexure from ground surface decreases with the increase of relative density of soil.
3. The rigid or flexible nature of pile is extremely dependent on slenderness ratio and pile head fixity. Pile of L/D less than 10 behaves like short rigid pile and more than 10 behaves like long pile.
4. Short pile undergoes significant negative displacement. The maximum negative displacement occurred at the base of the pile for short pile. The same is occurred in between inflection point and the base of pile for long pile in loose sand. The soil reaction is 46.80% more for short pile than long piles resting in loose sand.
5. The lateral displacement of long pile for loose and dense sand is reduced by 69.75% and 73.90% respectively when the pile head fixity changes from free to fixed head condition.

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