Effect of Soil Properties on the Structural Response of Laterally Loaded Piles

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Abstract. Piles in offshore structures are vulnerable to lateral loads induced by high wind effects in coastal regions in addition to axial loads from the dead weight of the structure itself. Earthquakes are another source of lateral loads on piles in structures like bridges, dams, and high- to moderate- rise buildings. This study addresses the effect of soil properties around the pile on the structural design criteria (bending moments, shear forces, displacements, and lateral earth pressure) in the piles under combined effect of axial and lateral loads. Two soil types were considered in this study; clay and sand with different stiffnesses for each. The study revealed that the maximum bending moment and maximum shear force induced within the pile sections increases as the soil stiffness increases for both of sand and clay soils. The study revealed that piles embedded in clayey soils exhibits an average higher buckling capacity than in sandy soils. The buckling load in clayey soil surpassed that of the sandy soil by a factor of 20. The study has also incorporated determination of the buckling loads for piles embedded in clayey and sandy soils.

Keyword: Laterally loaded piles; soil properties; pile buckling.

1. Introduction

Piles can be constructed under different soil conditions and could be subjected to multiple loading scenarios. In offshore structures, the piles can be exposed to combined axial from the structures dead weight they support in addition to lateral loads from the wind loads or earthquakes. The variable loading scenarios combined with complex soil conditions represent a real challenge for the engineers in prescribing a right behavior. H-piles are widely used in pile construction for various structures including bridges, wind turbine foundations, oil platforms, etc. H-piles are used due to their high flexibility and easiness of construction. The structural response of H-piles embedded in different soil conditions is not fully understood [1]. Many researchers described the behavior of laterally loaded piles under different soil conditions. Abdel-Mohti and Khodair [2] used the finite difference and finite element procedures to analyze soil-pile interaction. They have conducted a parametric study to show the effect of soil modulus of elasticity and the distribution of soil springs along the pile depth on modelling soil response on the pile. They have also compared the finite difference and the finite element solutions on the problem of laterally loaded piles. Muqtadir and Desai [3] studied the stress distribution around the pile groups utilizing a 3D finite element technique developed specifically for their work accounting the debonding and slip between the soil and the pile user thin layer interface element. They have also addressed nonlinearity in soil around the pile and its impact on the relative motions at the interface. Brown and Shie [4] used a 3D finite element method to model the laterally loaded piles and conducted a parametric study to highlight the effect of pile spacing, pile head boundary condition and pile section on the pile behavior. They have use Abaqus software to generate a 3D model for both of soil and the pile.

The problem of laterally loaded piles has also been addressed by many textbooks which provide a detailed survey of the research conducted [5, 6, 7].

This study aims at describing the structural response of H-piles under combined effect of axial load and lateral displacement for two soil types: clay and sand. Three structural criteria were considered: bending moment, shear force, earth pressure and displacement. Buckling of piles under these soil conditions was also addressed to predict the ultimate buckling load for each soil type. LPile [8] software was used to conduct all analyses.

2. Selection of soil types and pile dimensions

Two soil types were chosen for the purpose of comparison; sand and clay with three values of stiffness for each type. Several pile sections were chosen to study the effect of pile size on the structural response and on the buckling initiation. The pile length was chosen as 50 ft (15 m); this length represents the average length of H-pile in the construction practice of driven piles and also based on preliminary calculations conducted by the authors to determine the pile depth beyond which the displacement vanishes. Figure 1 shows typical pile profile considered in the study. Tables 1 and 2 show typical values for the clay cohesion and sand modulus respectively. A steel grade of ASTM A36 was used throughout the study because of the wide popularity of its usage in pile construction. The unit weight of the soil was assumed 100 psf. The pile head was assumed hinged and the bottom of the pile was kept fixed. A displacement of (3 inch) was applied at the pile head throughout the parametric study to study the variation of soil properties on the structural response. The modulus of elasticity of steel material was taken as 29000 ksi.

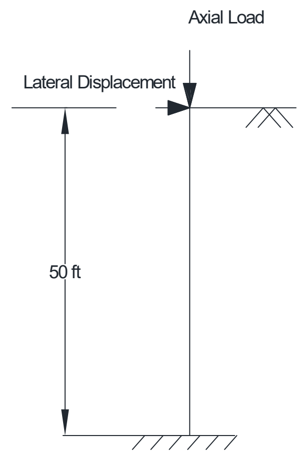


Figure 1. Typical pile profile problem

Table 1. Soil properties for clay and sand

Soil Type	Cohesion (psf)
Soft Clay	<1000
Medium Clay	1000-2000
Stiff Clay	2000-4000

Table 2. Representative values of k for stiff clay

	Undrained Shear Strength (psf)		
	1000-2000	2000-4000	4000-6000
k_s (pci)	500	1000	2000

3. LPile software

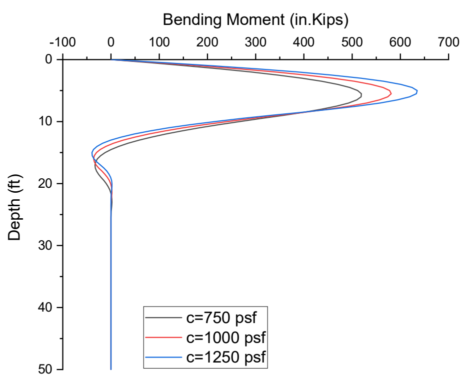
LPile is a finite difference-based program made by ENSOFT, Inc. for analysis of piles under combined effect of axial and lateral loading. It has also a capability of predicting the buckling load under different loading and boundary conditions scenarios. The pile in the program is assumed as a one-dimensional problem and the soil is simulated as a series of independent nonlinear springs. The stiffness and load-displacement of the soil depends mainly on the type and characteristics of the soil around the pile. The program is widely used by many design offices in the United States and Europe and has acquired accepted recognition.

4. Effect of soil parameters on the structural response

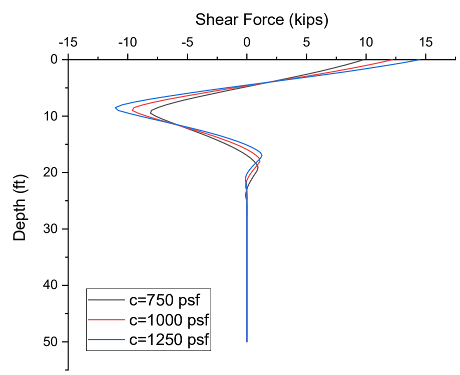
4.1. Effect of soil cohesion

Figure 2a and b represents the bending moment and shear force for HP 8x36 pile for three soil cohesion values 750, 1000, and 1250 psf which represents the range of the soft clay. The figures indicate that the maximum bending moment and maximum shear force increase as the soil cohesion increases. While the soil reaction is higher at high cohesion values (Figure 2c), pile displacement shows no significant change as the cohesion increases (Figure 2d). The reason for increased bending moment, shear force and soil reaction is attributed to the increased restraining effect of the soil against the pile which make stresses inside the pile material to increase. The displacement profile is similar for all cohesion values because the top displacement is the same for all cases considered.

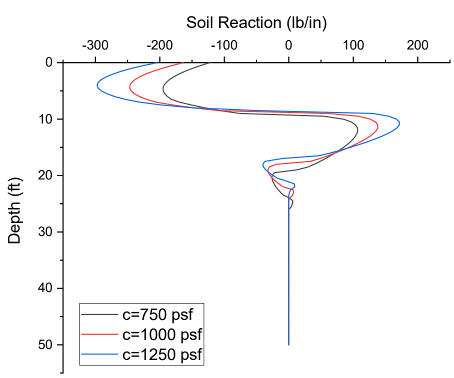
To investigate effect of pile stiffness on the structural response, three pile sections were selected for comparison (HP8x36, HP12x74, HP16x162). The soil cohesion was kept constant at 1000 psf. Figure 3 indicates that bending moment, shear force and soil reaction increases as the pile stiffness increases. The higher structural responses are attributed to the high moment of inertia of the section which resulted in creating higher moment and shear values.



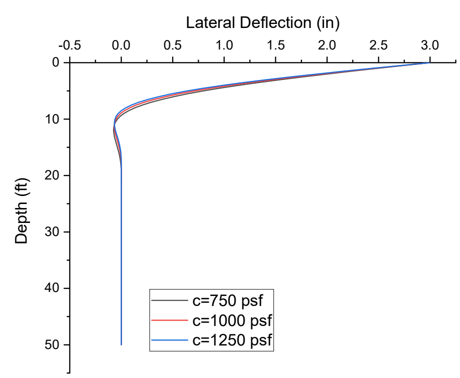
(a)



(b)



(c)



(d)

Figure 2. Structural response of HP8x36 piles embedded in cohesive soil. (a) Bending moment, (b) Shear force, (c) Soil reaction, (d) Lateral deflection

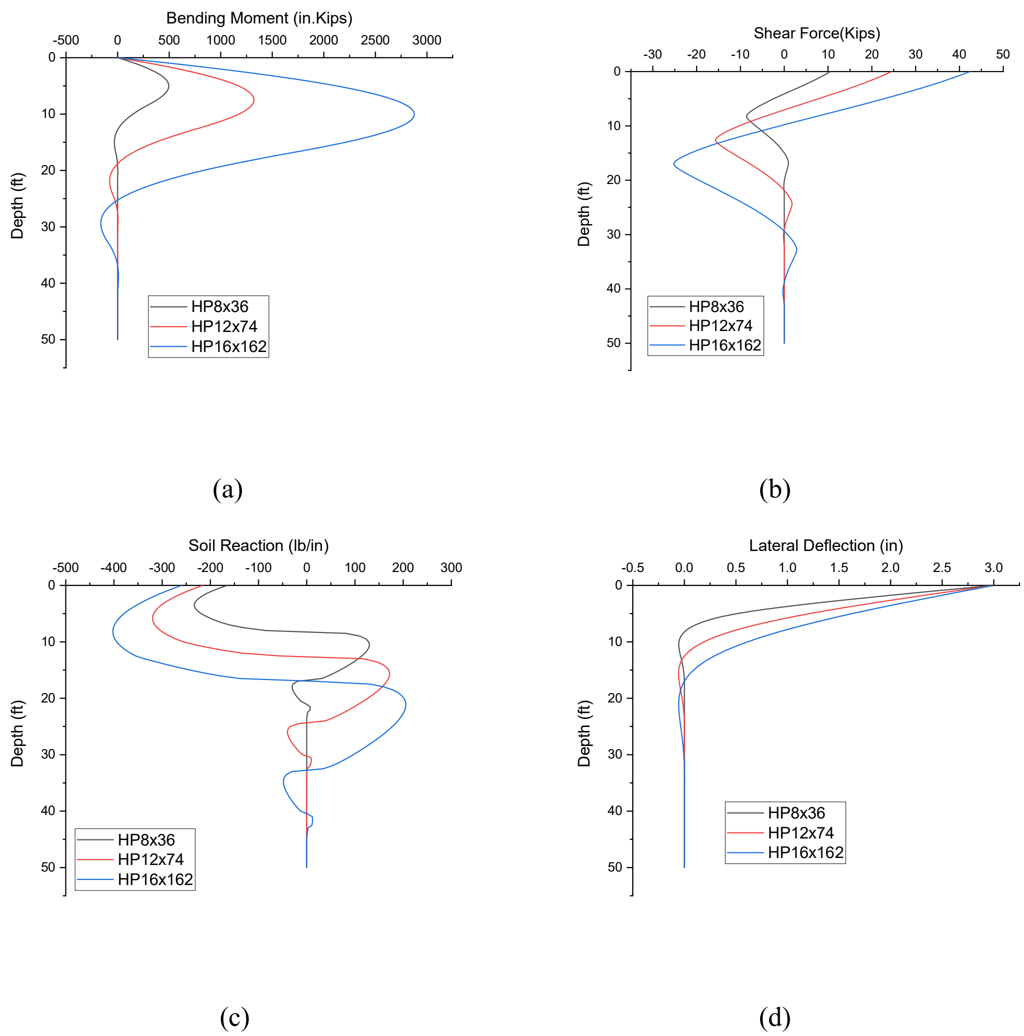


Figure 3. Structural response of multiple H-piles embedded in cohesive soil. (a) Bending moment, (b) Shear force, (c) Soil reaction, (d) Lateral deflection

Table 3. Representative values

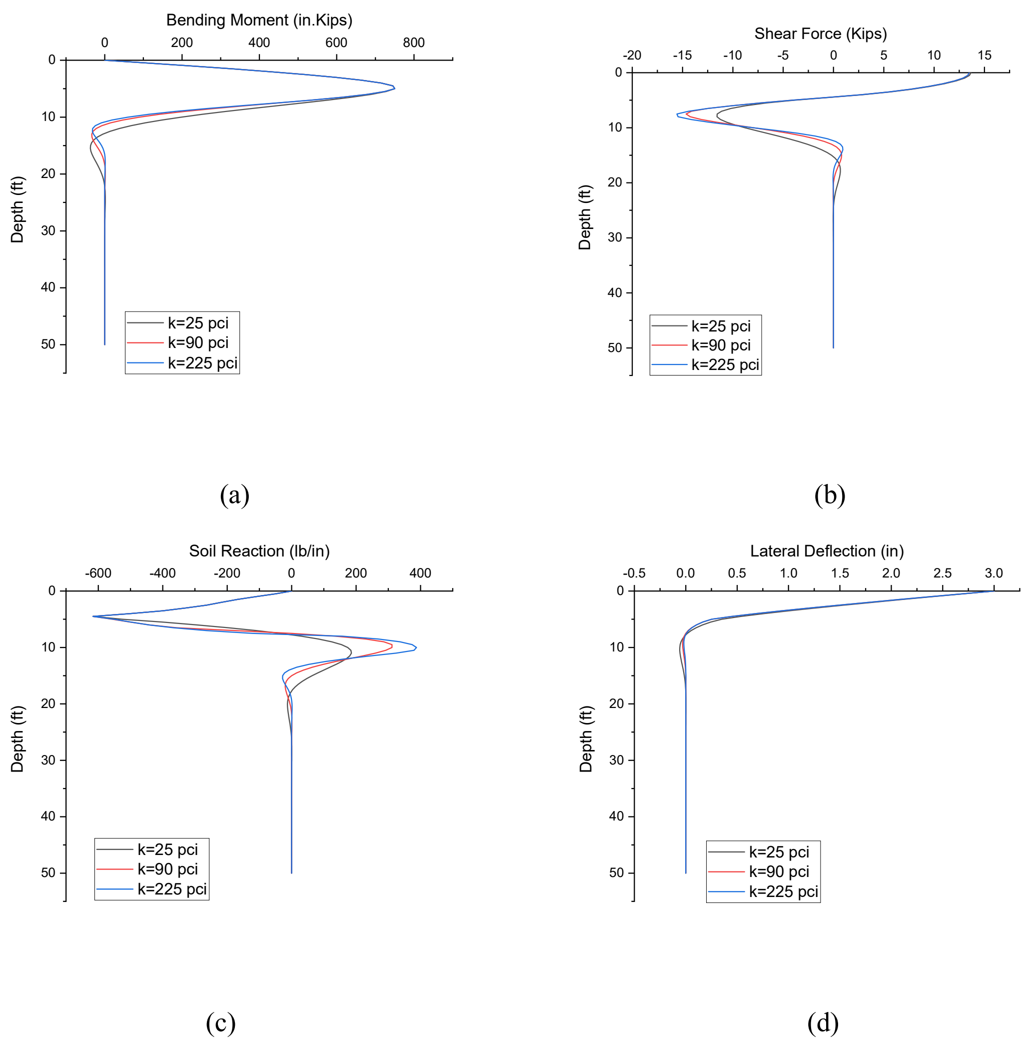
	Relative Density		
	Loose	Medium	Dense

K (pci)	25	90	225

4.2. Effect of sand stiffness

To investigate the effect of sand stiffness (k) on the structural response of laterally loaded piles, three values for sand stiffness was considered. These are 25, 90, and 225 pci for loose, medium and dense sand respectively as shown in Table 3. One pile section (HP10x42) oriented to the weak axis was chosen in a soil having a 100 pcf soil. An average angle of internal friction of the sand was chosen as 35°. Loading and boundary conditions were the same as in the case of cohesive soil.

Figure 4 indicates that the soil stiffness (k) has a very limited influence on the structural response of laterally loaded piles. The bending moment values were identical for all the three k values of sand, although there is a slight difference in case of shear force (Figure 4 a). The soil reaction showed higher values for the soil having higher stiffness (Figure 4c). However, the displacement showed no significant change and were similar to the cohesive soil (Figure 4d).



(a) (b) (c) (d)

Figure 4. Structural response of HP10x42 piles embedded in cohesionless soil. (a) Bending moment, (b) Shear force, (c) Soil reaction, (d) Lateral deflection

5. Pile buckling Analysis

Pile in a soil media delivers superstructure load to the stiff ground or bedrock. If the applied load on the pile exceeds the pile carrying capacity, the pile will undergo buckling and permanent failure. To investigate the buckling load for piles embedded in different soil conditions, several pile sections and soil types were subjected to the maximum axial load a pile can sustain before collapse triggers. Two soil types were selected: clay and sand, having different soil characteristics. Three pile sections were selected to investigate the effect of pile stiffness on the buckling capacity.

Figure 5 and figure 6 represent the buckling loads for clay soils with five cohesion values (500, 750, 1000, and 1250 psf). These values represent the range of soil cohesion for the soft clay. Two values for soil cohesion were considered for stiff clay:4000 and 8000 psf. The top of the pile was assumed hinged which means a zero moment at pile top and the maximum moment will generate at some depth below ground level. An incremental load was applied at the pile top combined with a very small lateral load to activate buckling initiation. Buckling was identified by increased lateral displacement as the axial load maintained constant.

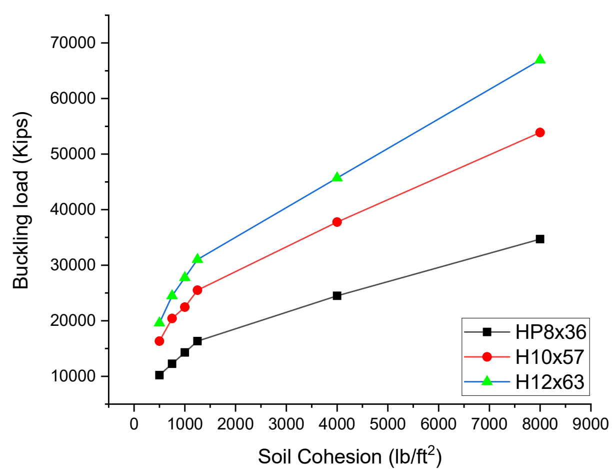


Figure 5. Buckling of piles in clayey soils

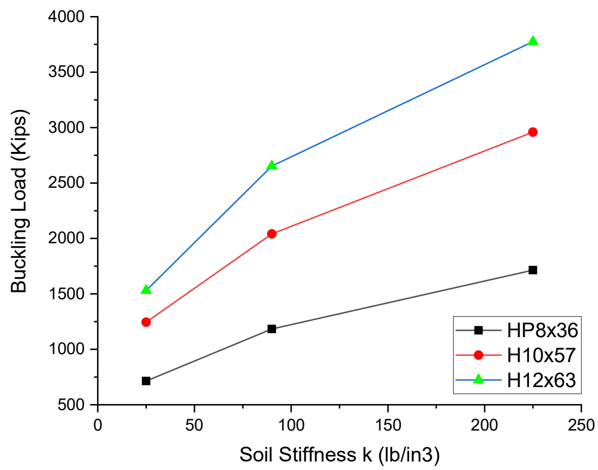


Figure 6. Buckling of piles in sandy soils

The figure indicates that as the soil cohesion increases, the buckling load increases proportionally. This is obvious as the soil stiffness provide lateral restraining effect for the pile and hence prevents the pile from buckling prematurely. In case of sand, three values were chosen to address buckling criteria: 25, 90 and 225 pci. These values cover sand relative densities range from loose to dense. As the sand stiffness increases, the buckling load also increases, similar to the clay cases. In general, pile embedded in a clayey soil showed higher buckling capacities than do in sandy soils. The buckling load in clayey soil surpassed that of the sandy soil by a factor of 20. This is attributed to the higher restraining effects imposed by clay on piles. This indicates that clayey soil provides better lateral restraining for the pile than sandy soil. In clayey soils, it can be seen from the graph that increasing the cohesion by a factor of 10 will result in a corresponding buckling load rise by a factor of 3. In case of sandy soil, increasing soil stiffness within a range of (25 -225) pci resulted in an increased buckling load by twice. For all HP sections, when the radius of gyration increased by a factor of 1.5 resulted in an increased buckling load by a factor of 2.3 for sandy soil and 2.6 in clayey soil. The unit weight of the soil was kept constant throughout the analysis and was taken as 100 pcf. The sand angle of internal friction was also kept constant as 35^o.

To get more insight about the effect of the soil on the buckling capacity, a FE model is constructed for the piles in section 5 without the soil effect using the FE package Abaqus (version 2019). The geometry and material properties were identical to the cases with the soil. The pile was modelled using 60 beam elements and elastic behavior was assumed geometric nonlinearity activated. Figure 7 shows the FE model of the typical pile considered. Figure 7 shows the buckling load capacities for the three piles and the corresponding axial displacement. The figure indicates that the piles without soil lateral support underwent a buckling failure at a very small load values compared to their counterparts in figure 5, for both of the soil types, clay and sand. The least value for pile buckling having a section of HP8x36 in sandy soil having a modulus of sand (k) of 25 lb/in^3 is 714 Kips while the corresponding value in a non-supported pile is 12.4; a difference by a factor of 57. The highest buckling load which was obtained for pile HP12x63 at clayey soil having a cohesion of 8000 lb/ft^2 was 670,000 Kips compared to 201.9; a difference by a factor of more than 3000. Kips for non-supported pile. This suggests that soil around the pile boosts the pile buckling capacity depending on its type and consistency. The clayey soil with higher cohesion highly influences the pile buckling than does sandy soil with small densities. It is highly recommended, though, to stabilize the soil supporting the pile to promote pile carrying capacity.

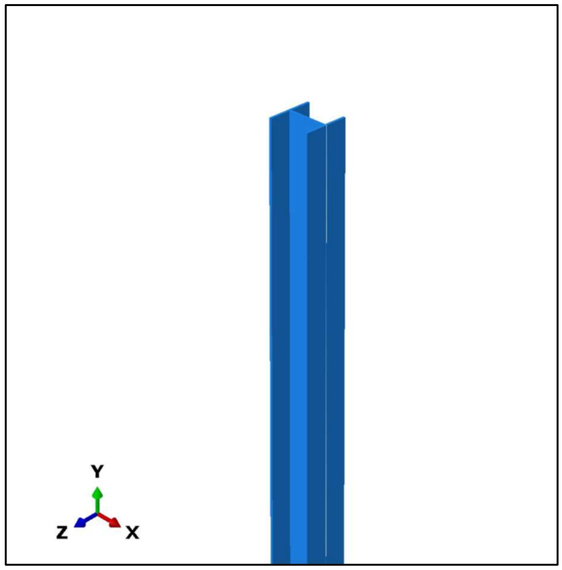


Figure 7. Finite element model of typical pile without soil

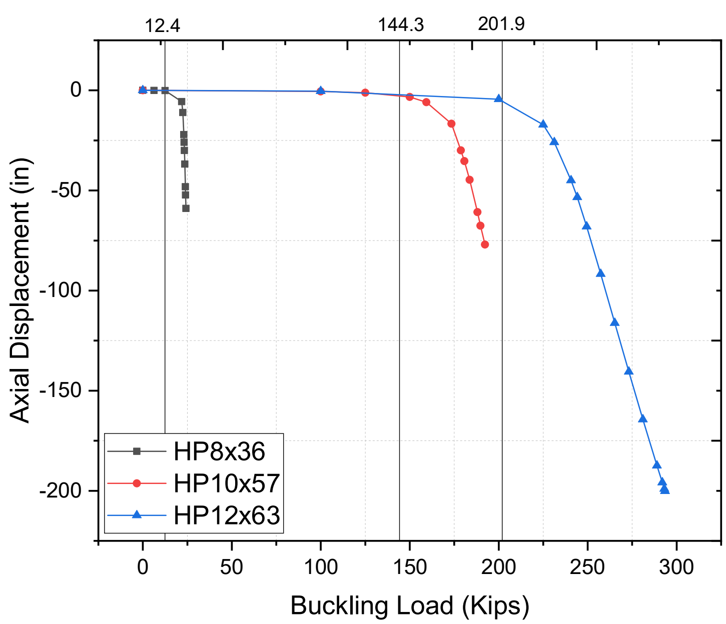


Figure 8. Buckling of piles without soil versus axial displacement

6. Conclusions

Based on the study conducted herein, the following conclusions were drawn:

1. The maximum bending moment and maximum shear induced in the pile sections increases as the soil stiffness (c and k) increases for both of sand and clay soils.
2. Piles embedded in clayey soils exhibited an average higher buckling capacity than in sandy soils. The buckling load in clayey soil surpassed that of the sandy soil by a factor of 20. This is attributed to the higher restraining effects imposed by clay on piles.
3. In clayey soils, increasing the cohesion by a factor of 10 will result in a corresponding buckling load rise by a factor of 3.
4. In sandy soil, increasing soil stiffness within a range of (25 -225) pci resulted in an increased buckling load by a factor 2.
5. The increase in the radius of gyration values for HP sections by a factor of 1.5 resulted in an increased buckling load by a factor of 2.3 for sandy soil and 2.6 in clayey soil.
6. Soil surrounding the pile contribute in raising the buckling capacity of the pile by a factor of 57 for loose sandy soil to 3300 for very stiff clay. It is recommended to stabilize the soil surrounding the pile to promote pile carrying capacity.

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