Numerical Modeling of Interface Between Soil and Pile to Account for Loss of Contact during Seismic Excitation

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ABSTRACT:
This paper presents a methodology to understand the interface behavior of soil and pile under transient loading. Previous works by Trochanis (1991), Bently and Naggar (2000) and others gave an insight to the problem. But this paper illustrates the research methodology developed to understand the dynamic behavior of pile and soil by taking the soil yielding effects and also the interface effects. A detailed parametric study has been done to understand the behavior of the same by varying the length of the pile for various soil conditions. For the purpose of comparison, soil model size was taken as 15m x 10m x 11m with pile cross section as 0.5 X 0.5 m and length of pile as 10m. For this we have developed a program for modeling the soil pile structure interaction using three dimensional Finite Element Method in MATLAB R2009a, the details of the same have been given in this paper along with the validity of it with benchmark problems in the literature.

Keywords: Finite Element Method, Piles, Soil yielding effects, Interface effects

1. INTRODUCTION

Experiences from past earthquake disasters clearly shows that when a soil pile structure model is subjected to seismic excitations, the soil surrounding the pile may be compressed laterally such that a soil pile gap separation may develop. These soil pile gap separations have been observed in the past both in field and laboratory tests. After 1995 Kobe earthquake the soil pile gap was observed in reclaimed port Island and also in 1989 Loma Prieta earthquake, the soil pile gap developed along the Struve Slough crossing (Chau et al., 2009). In view of this there is a need to study the complex behavior of soil-pile interaction problems using numerical methods.

In the past, the work on pile soil interface has been done by modeling the separation, sliding, debonding or rebonding by using special contact elements called Interface elements (Trochanis et al., (1991 a), Trochanis et al., (1991 b), Bentley and Naggar (2000), Ozkan et al., (2002), Maheshwari et al. (2004)). But in this study a simple technique has been used to capture the interface behavior of sliding, debonding or rebonding. The details of which has been given in the following sections along with its validity with numerical results from the literature.

The main objective of this work is to contribute to the understanding of the seismic performance of pile considering the complex dynamic interaction between the pile foundation and the soil. For this Finite

Element Method is used to model pile soil interaction by programming in MATLAB R2009a using Direct approach. The main objective of this paper is to focus on the methodology used for developing this program along with modeling the nonlinearities of soil and the interface of soil and pile. After developing the FEM model it has been verified against available solutions for benchmark problems in the literature including piles embeded in elastic, elasto plastic soils, with and without interface elements. Also a detailed parametric study has been done to understand the behavior of the same by changing the length of the pile for various soil conditions.

2. THREE DIMENSIONAL FINITE ELEMENT MODEL

2.1 Model Formulation

Full three dimensional geometric model used for soil pile system is shown in Fig. 1. The pile has a square cross section and is fully embedded in the soil, and is socketed in the bed rock. The soil and pile were modeled using eight-node hexahedral elements (Fig. 2a) called brick element. Each node has three degrees of freedom that is translation u_x in x, translation u_y in y direction and translation u_z in z direction.

The soil is assumed to be Clay and the piles are made of concrete and have square cross section with each side 0.5 m. The length of pile 10m with pile slenderness ration of 20. The material properties of the pile and soil are given in Table 1.

2.2 Boundary Condition

For static and dynamic analysis, the bottom edge is fully constrained in all three directions to model the rigid bed rock. The nodes along the top surface and four lateral surfaces of the mesh are free to move in

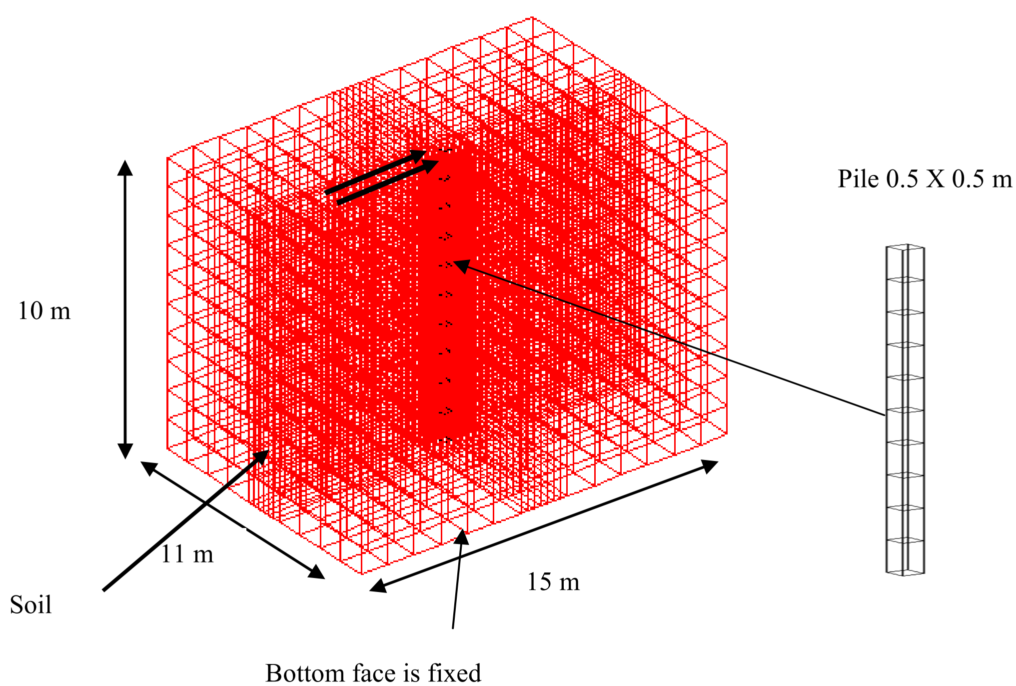


Figure 1. 3D pile soil system considered for the study

Table 2.2.1. Material Properties

Material Properties	Modulus of Elasticity (KN/m^2)	Poisson's Ratio	Yield Strain
Clay	11.78 X10^3	0	0.0002
Concrete	25 X 10^6	0	0.0035

all directions. For dynamic analysis, the four lateral faces have been modeled with viscous dampers (dashpots are used to represent the radiation damping) to represent the continuity of the soil deposit as an infinite half space. Viscous dampers are attached on the side faces of soil in all the three x, y and z directions as shown in Fig. 2b. The damping coefficients given by Lysmer and Kuhlemeyer (1969) for normal and perpendicular directions are used.

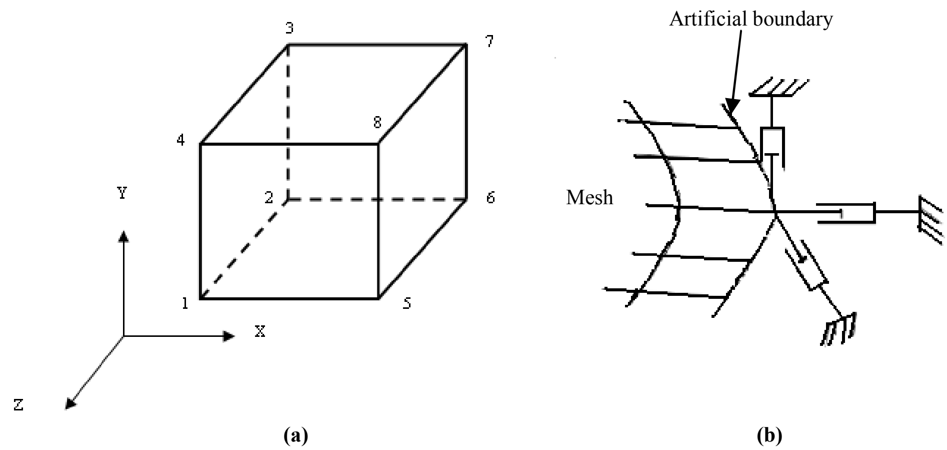


Figure 2. (a) Eight-node Hexahedral element (b) Viscous damper on the boundary

2.3 Mohr Coulomb Yield Criteria

The Mohr Coulomb Yield criterion which takes into account the influence of hydrostatic stresses is used. The yield function is written in terms of stress states and two material properties the cohesion c and angle of internal friction φ. For principal stresses in the order $\sigma_1 > \sigma_2 > \sigma_3$, the Mohr Coulomb Yield function is (assuming compression as negative)

$$F = \sigma_1 - \sigma_3 - (\sigma_1 + \sigma_3)\sin\varphi - 2\, c\, \cos\varphi \qquad (2.3.1)$$

In principal stress space, the yield surface for Mohr Coulomb criterion has the form of an irregular hexagonal pyramid as shown in Fig. 3. If a material such as concrete is studied and the strength parameters σ_c and σ_t are known then following equations should be used to find c and φ needed by Mohr Coulomb yield function.

$$c = \frac{\sigma_t}{2}\sqrt{\frac{\sigma_c}{\sigma_t}} \qquad (2.3.2)$$

$$\varphi = \frac{\pi}{2} - 2\tan^{-1}\left(\sqrt{\frac{\sigma_t}{\sigma_c}}\right) \qquad (2.3.3)$$

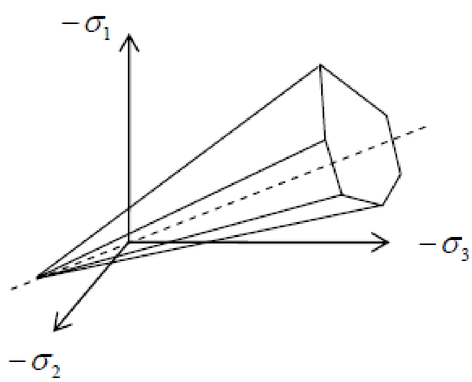


Figure 3. Mohr Coulomb Yield surface in principal stress space

The approach of analysis for material nonlinear effects includes an incremental analysis. Here a load history is considered and a response history is obtained by applying load in increments. The load increments are to be small so that the increments in displacements, strains and stresses are small, and the errors are also small (Madhu 1993). The details of the incremental analysis can be found in any standard FEM book.

2.4 Pile – Soil Interface

In any soil structure interaction analysis, relative movement of structure with respect to soil can occur and the modeling of this behavior is the most challenging part. In this thesis the separation / debonding of pile and soil (as shown in Fig. 4a) along with the rebonding (as shown in Fig. 4 b) of pile and soil has been modeled by checking for the tension in soil elements adjacent to pile. For that purpose the normal stresses in horizontal direction of all the soil elements adjacent to pile should be checked for separation or debonding for each and every load step/iteration that is

$$\sigma_x < 0 \quad \text{(Tensile)} \qquad (2.4.1)$$

In the separation mode, all those elements that are in tension does not impart any stiffness to the system (as shown in Fig. 4.3c) in horizontal direction, so accordingly the normal stresses are calculated with changed stiffness and the residual which have dimension of stress, are converted into loads that are applied to system during iterative corrections, the procedure for convergence is same as used for material nonlinearity case. It is assumed that separation occurs in the direction of loading only and the soil and pile are still in contact in the other direction. In rebonding state all the elements regain the stiffness and impart stiffness to the system.

$$d\sigma = D_{new}\ d\varepsilon \qquad (2.4.2)$$

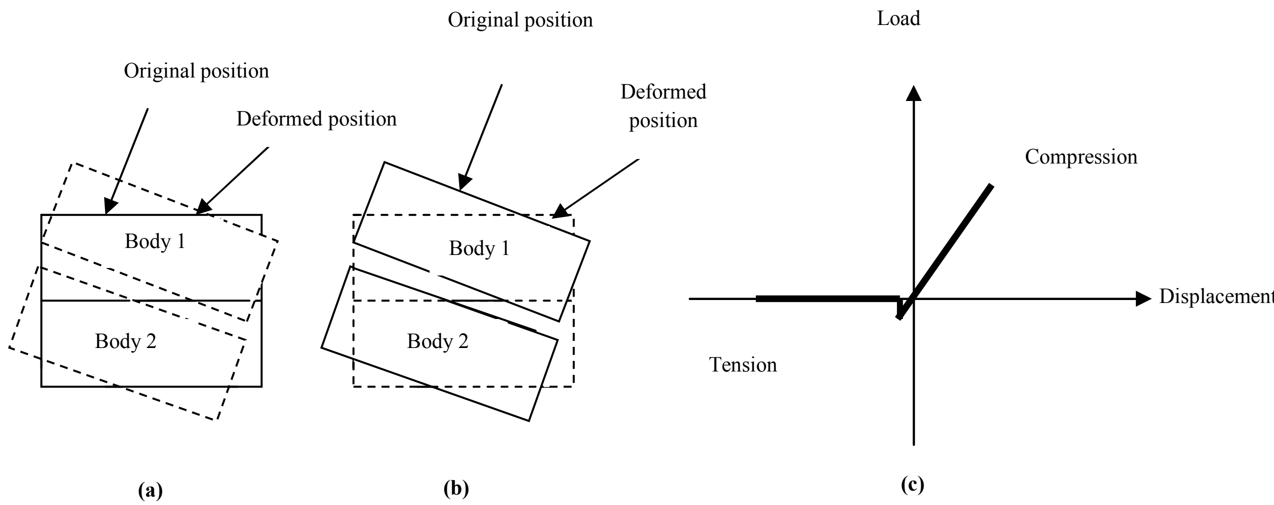


Figure 4 **a.** Separation or debonding at interface
b. Rebonding at interface
c. Stiffness envelope at interface.

2.5 Loading Conditions

The state of stress in the pile–soil system in actual in situ conditions was replicated as an initial loading condition prior to any additional dynamic or static external load. That is, geostatic stresses were modeled by applying a global gravitational acceleration, *g*, to replicate vertically increasing stress with an increase in depth.

Static load is applied as load at the pile head in level with ground surface. For dynamic case, according to Nair (1969), there are three methods of accounting earthquake force, in which one of the method is applying the sinusoidal load at the surface. So in this study to account for dynamic load an sinusoidal load is applied at the surface.

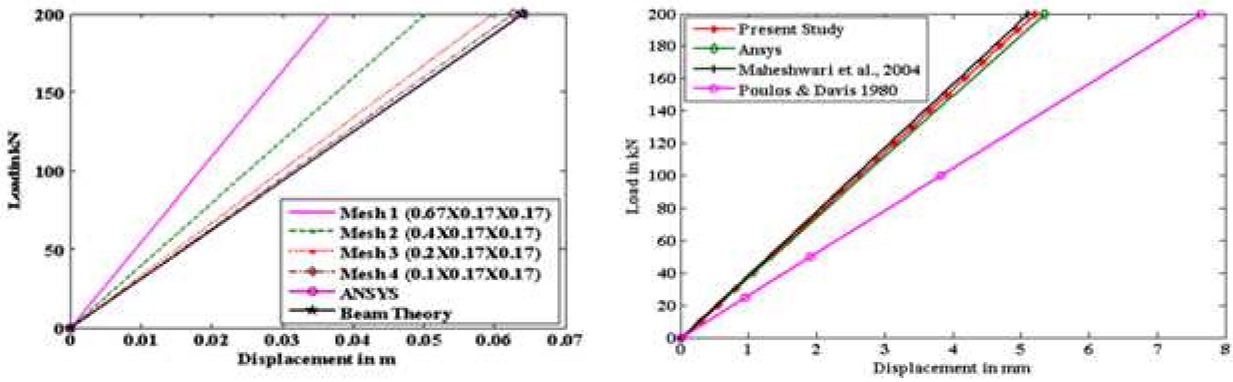
3. VERIFICATION OF FINITE ELEMENT MODEL

The static performance of the model was verified against exact available solutions for benchmark problems including piles in elastic and elasto plastic soils.

3.1 Linear Analysis

In the linear analysis verification process is done in two steps only for pile and the other one when pile is embedded in soil. The pile mesh was verified by considering the pile as fixed cantilever in air (no soil). Lateral deflections resulted from a static load for different pile meshes were compared with those from 1D Beam Flexure Theory as shown in Fig. 5a. As shown in the figure the results were converging to the Beam Flexure Theory when mesh is becoming finer.

In the linear analysis when pile is embedded in soil the verification is done by checking the results with the analytical solution of Poulos and Davis (1980) and the Numerical results of Mahsehwari et al., 2004 and ANSYS. The comparison of all the three results mentioned above for linear elastic response under lateral loading at pile head are shown in Fig. 5b. Figure shows that results for elastic case are in good agreement with those obtained by Mahsehwari et al., 2004 and ANSYS, but deflection shown by present model is slightly less that those obtained by Poulos and Davis (1980). The same variation of results with analytical solution was even observed by Maheshwari et al., in their studies. The mesh that yields the closest match that is Mesh 2 of 0.5 X 0.5 m element size is used in rest of the study.



(a) (b)

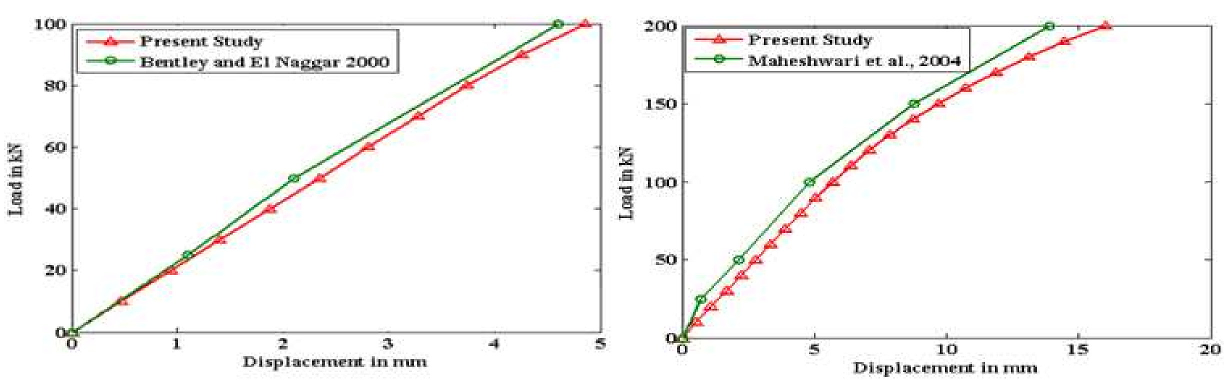
Figure 5. Response of pile (a) As Cantilever (b) Embedded in soil.

3.2 Nonlinear Analysis

A nonlinear soil model as mentioned above has been used to introduce the effect of plasticity. To evaluate the effect of soil plasticity on pile response, the soil was modeled as a homogeneous elastic medium and an elastoplastic using the bilinear model. This model was with zero strain hardening and therefore progressive yielding was not considered. In nonlinear analysis verification is done for two cases that is when interface element is not present and when interface element is present.

In nonlinear analysis without interface element, it is assumed that soil and pile are perfectly bonded. When interface element is not present verification is done by comparing the results with Bentley and El Naggar (2000) (Fig. 6a). The results show that there is a small difference between the results obtained by present study and those obtained by other approach. This may be attributed to the use of different model for soil plasticity (Drucker Prager model).

In nonlinear analysis with interface element, the verification is done by comparing the results with Maheshwari et al., 2004 (Fig. 6b). The results show that there is a small difference between the results



(a) (b)

Figure 6. Response of single socketed pile for plastic soil case (a) Without Interface Element (b) With Interface Element.

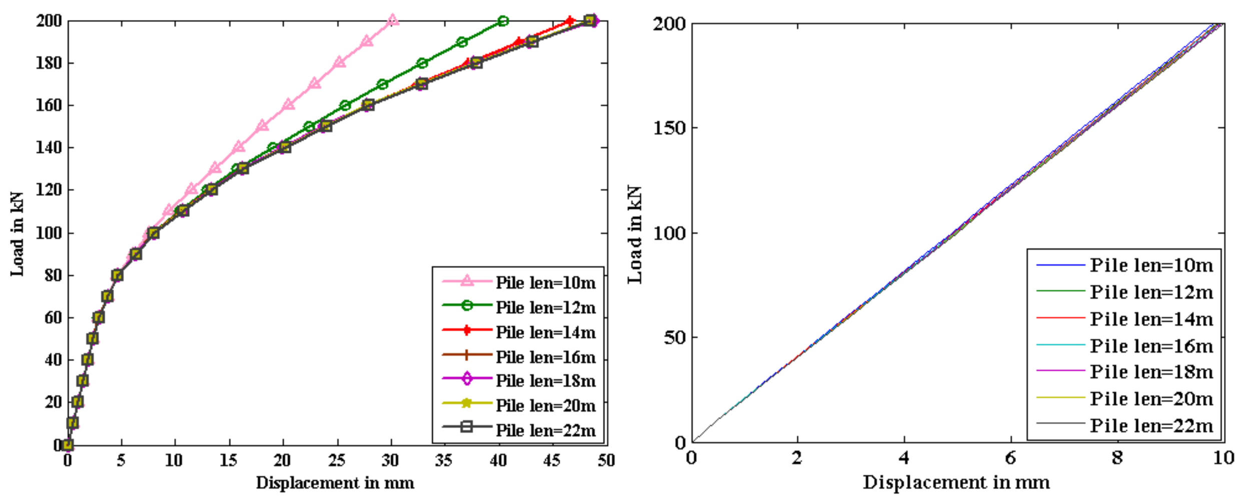
obtained by present study and those obtained by other study. This may be attributed to the difference in modeling of initiation of gapping/separation. In the present study, separation is initiated when tension is detected in soil elements adjacent to pile, where as the other approach used a special contact element at the soil pile interface.

4. EFFECT OF INTERFACE MODELING ON PILE BEHAVIOR

After checking the accuracy of the model for both linear and nonlinear cases with and without interface elements, in this section a parametric analysis is done by varying the pile length for various soil conditions in both static and dynamic cases.

4.1 Static case

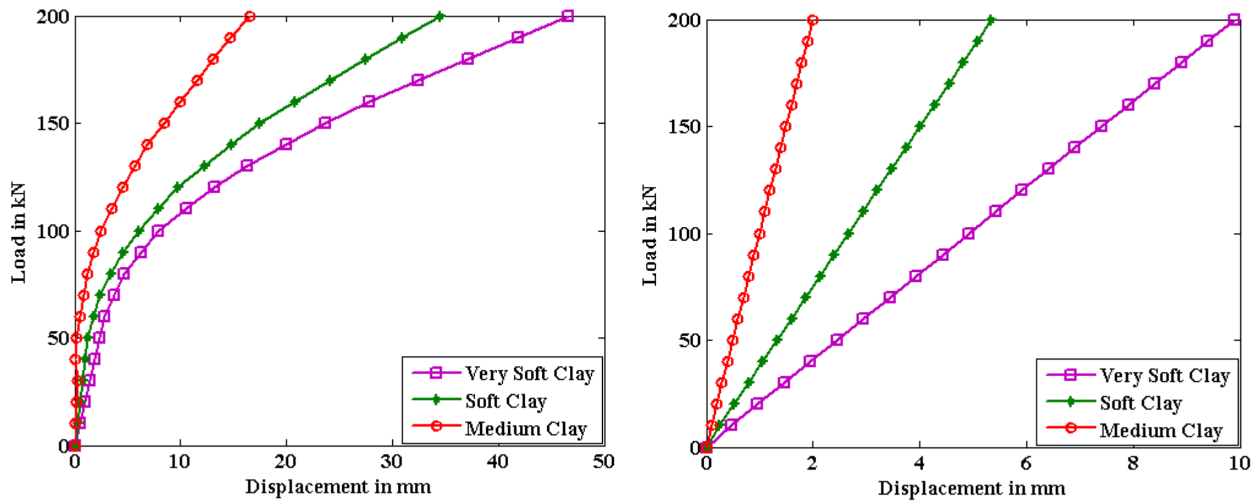
For the static case, the model shown as above is considered and the load is applied at pile head as a monotonic load and nonlinear analysis with and without interface elements has been done for varying pile lengths and soil conditions. Fig. 7 shows the response of pile tip without (Fig. 7a) and with interface element (Fig. 7b) for very soft clay. From figure it has been observed that as the pile is becoming slender the displacements are increasing that is pile is behaving as flexible member and after certain length of pile the displacements are becoming constant. But this increase in displacement for various pile lengths is not observed in interface modeling case as here the soil elements are not going to nonlinear state but only gap is developed between the pile and soil. Similar kind of behavior was observed for soft and medium clays. Fig. 8 shows the response of single socketed pile for various soils without (Fig. 8a) and with interface element (Fig. 8b). The general trend of very soft clay having more displacement when compared to soft and medium clay is observed in both cases of without and with interface elements.



(a) (b)

Figure 7. Response of single socketed pile for plastic soil case of very soft clay for varying lengths of pile (a) Without Interface Element (b) With Interface Element.

Fig. 9 shows the pile and adjacent soil elements of very soft clay, the highlighted elements represent all those elements that are in tension. From the results it has been observed that as slenderness of pile increases soil elements on either side of the pile are in tension that is a gap is developed. So while designing any slender piles care must be taken in designing the tip and head of pile as during lateral loading at the pile head confining pressure from soil at these places is lost. The same behavior is observed in case of soft clays also. Fig. 10 shows the pile and adjacent soil elements of medium clay, the highlighted elements represent all those elements that are in tension. From the results it has been observed that as slenderness of pile increases soil elements on either side of the pile and also middle soil elements are in tension that is a gap is developed. From the results it has been observed that depending on the type of soil in which pile is installed care must be taken in designing the pile.



(a) (b)

Figure 8. Response of single socketed pile for various soils in plastic state
(a) Without Interface Element (b) With Interface Element.

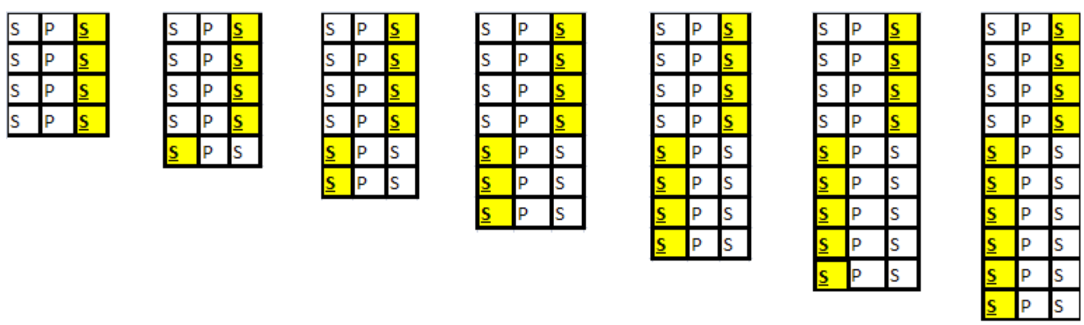


Figure 9. Representation of Pile and adjacent soil elements for plastic soil case of very soft clay for varying lengths of pile (with Interface Element)

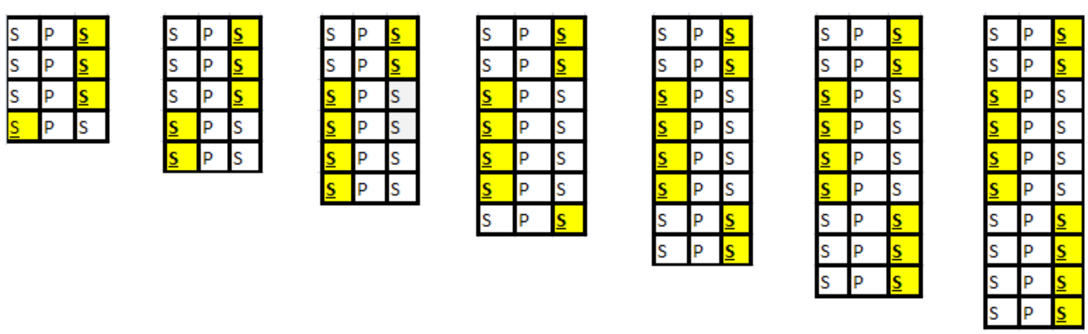


Figure 10. Representation of Pile and adjacent soil elements for plastic soil case of medium clay for varying lengths of pile (with Interface Element)

4.2 Dynamic case

For the dynamic case, the model shown as above is considered and the load is applied at pile head as a sinusoidal load. Fig. 11 shows the pile and adjacent soil elements of very soft clay, the highlighted elements represent all those elements that are in tension. From the results it has been observed that as loading continuous gap is developed on either sides of the pile leading to loss of confining pressure from soil along both sides of pile. Fig. 12 shows the pile and adjacent soil elements of medium clay, the highlighted elements represent all those elements that are in tension. From the results it has been observed that soil elements on either side of the pile and also middle soil elements are in tension that is a gap is developed. So while considering the dynamic loads in design irrespective of the type of soil in which pile is installed care must be taken for full length of pile.

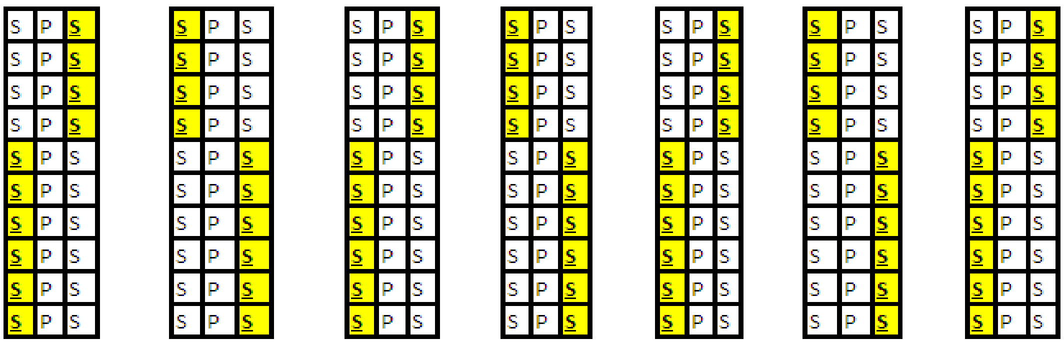


Figure 11. Representation of Pile and adjacent soil elements for plastic soil case of very soft clay for one length of pile (with Interface Element)

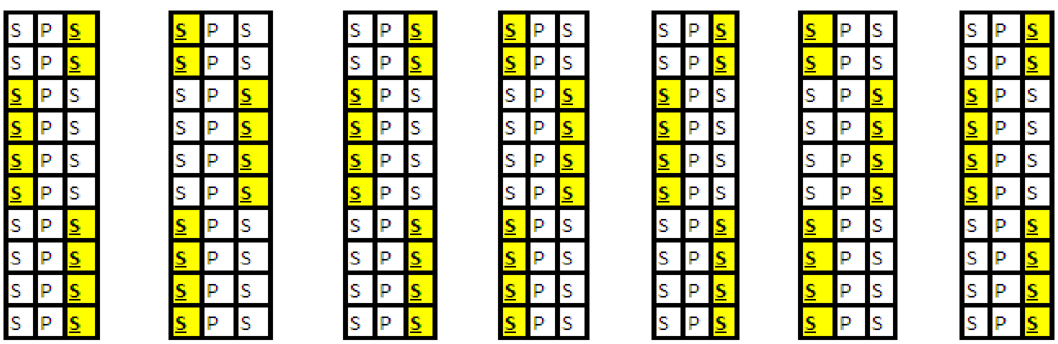


Figure 12. Representation of Pile and adjacent soil elements for plastic soil case of medium clay for one length of pile (with Interface Element)

CONCLUSIONS

In this study a research methodology is developed for modeling the soil pile structure interaction using three dimensional Finite Element Method in MATLAB R2009a.

The program includes the soil and pile nonlinearity along with the modeling of interface between pile and soil. For nonlinear pile and soil model Mohr Coulomb yield criteria is used with the material behavior as elastic perfectly plastic. In case of interface modeling instead of using special contact elements, a simple technique is used to model the debonding and rebonding of pile and soil.

In this a parametric study is done to understand the interface behavior by varying the length of pile for various soil conditions. From the results it has been observed that as the pile is becoming slender the displacements are increasing that is pile is behaving as flexible member and after certain length of pile the displacements are becoming constant.

In static case from the results it has been observed that depending on the type of soil in which pile is installed care must be taken in designing the pile tip or head. But where as in dynamic case irrespective of the type of soil in which pile is installed care must be taken for full length of pile.

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