Numerical Simulation to Study the Effect of Combination Vertical Load and Lateral Load on Pile Performance in Cohesionless Soil

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Abstract

Pile foundation is widely subjected to both vertical and lateral loads. The available design procedure assumes that the effect of these two loads is independent of each other and hence the pile design is carried out separately for vertical and lateral loads. The traditional methods for analysis of piles according to sub-grade reaction methods also do not consider the effect of interaction between the different load directions. The effect of combination vertical loads and lateral on pile performance that installed in cohesionless soils is considered in this paper through three-dimensional finite element analyses. In the numerical model, the pile was treated as a linear elastic material and the soil was idealized using the Mohr-Coloumb constitutive model. The results from the analysis of single piles under combined vertical and lateral loads are studied in this paper. The influences of related parameters such as shear strength (angle of internal friction and dilatation angle) of soil in term of loose and dense sands and pile/soil interface friction coefficient have also been studied in this work. The results have shown that the combination vertical load and lateral has a significant effect on the pile performance that installed in cohesionless soil.

Key Words: FEM model, Pile, cohesionless soil, lateral load, deflection, interface friction.

المحاكاة العددية لدراسة التأثير المتداخل للحمل الرأسي و الحمل الجانبي على استجابة الركيزة المثبتة في التربة غير المتماسكة

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الملخص

أسس الركائز غالباً ما تتعرض إلى أنواع الأحمال الرأسية والجانبية. أن طريقة التصميم المتوفرة والمستخدمة حالياً تفترض أن تصميم الركائز تحت تأثيرهذه الأحمال يجب ان يتم بشكل منفصل لكلا الأحمال الرأسية أوالجانبية. الطرق التقليدية الخاصة بتحليل الركائز وفقا لطرق رد فعل التربة الطبيعية أيضا لا تأخذ بنظر الأعتبار تأثير دمج كل من الأحمال ذات الأتجاهات المختلفة. لذلك فأن تأثير دمج كل من الأحمال العمودية والاحمال الجانبية اللذان تتعرض له الركيزة المثبتة والمغروسة في التربة الغير متماسكة تم أخذها بنظر الأعتبار ودراستها وتحليلها بأستخدام طرق المحاكاة العددية لنموذج ممثل بركيزة ثلاثية الأبعاد. تم في هذا النموذج تمثيل الركيزه على انها تتصرف بطريقة خطية ومرنة اما التربة المحيطة بالركيزة فقد تم تمثيل تصرفها باستخدام دالة أذعان موهر- كولومب. تم في هذه الدراسة تحليل ألنتائج المستحصلة من تعرض أساسات الركائز لتأثير دمج كل من الأحمال العمودية والجانبية. بلأضافة الى دراسة تأثير قوة القص للتربة والمتمثلة بزاوية الاحتكاك الداخلي وزاوية تمدد حبيبات من حيت حالات التربة المفككه والمرصوصة وكذلك معامل الأحتكاك البيني بين الركيزة والتربة تم دراسة تأثيره ايضاً. وقد أظهرت النتائج أن دمج كل من الحمل العمودي والحمل الجانبي اللذان تتعرض له الركيزة المثبتة في التربة غير المتماسكة له تأثير كبير على ادائها.

Introduction

Piles have been used extensively for supporting vertical and lateral loads for various structures including heavy buildings, transmission lines, power stations, and highway structures. These piles are not only used to support vertical loads, but also lateral loads and combination of vertical and lateral loads. (Rajagopal and Karthigeyan 2011). According to the current design practice, piles are independently analyzed first for the vertical load to determine their bearing capacity and settlement and for the lateral load to determine the flexural behaviour. This approach is valid only for small lateral loads, however, in case of coastal/offshore applications, the lateral loads are significantly high of the order of 10–20% of the vertical loads and in such cases, studying the interaction effects due to combined vertical and lateral loads is essential, which calls for a systematic analysis (Moayed et al. 2012).

Several investigators have attempted to study the behaviour of piles and pile groups under pure lateral loads [(Mahmoud and Burley 1994), (Abbas et al. 2008), (Basu et al. 2008)]. Besides, with the advent of latest generation computers, it is now possible to investigate the effects due to non-linearity and elasto-plasticity of soil medium, asymmetric loading on piles etc. using 2-dimensional finite element analysis [(Brown and Shie 1991), (Yang and Jeremić 2002), (Chik et al. 2009) and (Mardfekri et al. 2013)]. However, there is hardly any concerted effort to study the influence of vertical load on the lateral response of piles and the literature on combination of vertical and lateral loads is scanty. The limited information on this aspect based on the analytical investigations (Davisson and Robinson 1965) and (Banerjee and Davies 1978) reveals that for a given lateral load, the presence of vertical load increases the lateral deflection. However, laboratory (Jain et al. 1987) and field investigations [(Sorochan and Bykov 1976) (Zhukov and Balov 1978) (Pando et al. 2003)] suggest a decrease in lateral deflection under the presence of vertical loads. Anagnostopoulos and Georgiadis, (1993) have reported that the modified status of soil stresses and local plastic volume changes in the soil continuum under combined vertical and lateral loads cannot be accounted for in general by the conventional subgrade reaction and elastic half space methods of analysis. Trochanis et al.,(1991) attempted to study the behaviour of a pile under combined vertical and lateral loads based on ٣-dimensional finite element method. The emphasis was mainly focused on the influence of lateral load on the vertical response of a pile rather than the influence of vertical load on the lateral response of piles. However, since piles are not often structurally designed to resist lateral loads, the lateral response of piles is more critical and interesting for design engineers. In view of the above stated issues, the present paper focuses on the effect of vertical load on the lateral response of piles. The effects of factors such shear strength (angle of internal friction and dilatation angle) of soil in term of loose and dense sands and pile/soil interface friction coefficient are highlighted.

Numerical Model

Recently, there is a growing number of mature FEM commercial software in international market (e.g Adina, Crisp, Ansys, Abaqus and Plaxis). Among them Abaqus and Ansys are the widely used FEM software in the geotechnical engineering and Abaqus is one of these software's dealing with elastic-plastic, nonlinear and contact problems. Therefore, Abaqus software is adopted to analyse the effect of combined vertical load and lateral load behaviour of single pile embedded in cohesionless soil. The schematic diagram of the single pile subjected to vertical load and lateral load is shown in Figure 1.

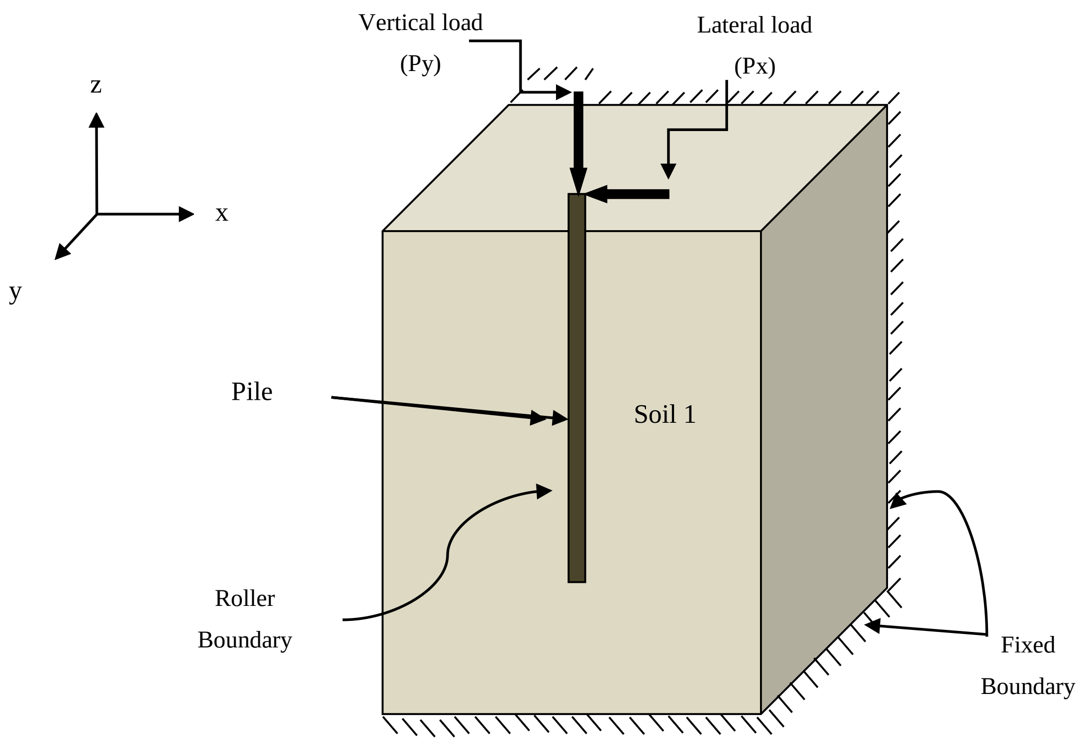

Figure 1: Schematic Diagram of the Axisymmetric Pile/soil model Subjected to Vertical and Lateral Loads

The solid elements were used to model the pile and the soil elements using 8-node linear brick, reduced integration, and hourglass control. The material behaviour of the concrete pile was assumed to be linear elastic. The surrounding sand is described by elasto-plastic material obeying Mohr-Coulomb failure criterion. A pile diameter of D=1.5 m and 35 m length was considered. The material behaviour of the pile was assumed to be linear elastic with the parameters E=25000 MPa (Young's modulus) and ν=0.2 (Poisson's ratio) for concrete. The set of soil properties for both loose and dense cases considered are shown in Table 1. The soil properties for loose and dense states were arrived at using correlations between SPT N-values and Young's modulus for soil (Bowles 1988).

Table 1: Material parameters used for soil

Property	Loose sand	Dense sand
Young Modulus, E (MPa)	16.0	50.0
Poisson's ratio, υ	0.30	0.30
Internal friction, ϕ^o	27	35
Dilatation angle, ψ^o	5	11
Unit weight γ (kN/m^3)	17	21

The contact behaviour at the pile-soil surface was modeled by "hard" contact in normal direction and Coulomb friction in tangent direction. The Mohr-Coulomb model is based on plotting Mohr's circle for states of stress at yield in the plane of the major and minor axis, (σ_1 and σ_3) respectively (Verruijt and Van Baars 2007). The yield line is the best straight line that touches these Mohr's circles (Figure 1).

There is no tension sustained between pile and sand and no slip occurred when tangential shear stress is lower than the shear resistance determined by normal pressure and friction coefficient of interface. The friction interface angle of pile-soil is set as 0.75 times of internal friction angle of sand.

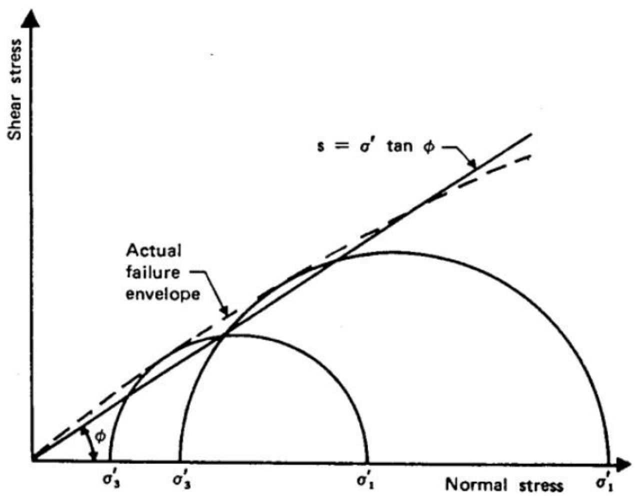

Figure 1: Mohr-Coulomb Failure Criterion

Model features

For the investigation of the influence of vertical loads on the lateral response of piles installed in sandy soil, a three-dimensional (3-D) numerical model was established. The computations were done using the finite element program system ABAQUS. Due to the symmetric loading condition only a half-cylinder representing the sub-soil and the pile was considered. For that, an idealized homogeneous soil consisting of loose and dense sands were considered. Due to the symmetric loading condition only a half-cylinder representing the sub-soil and the pile was considered. The boundary condition of the both sides of model was 10 times that of the pile diameter (Vipulanandan et al. 1989). The distance between the bottom of pile and soil bottom boundary is 12 m. With these model lengths the calculated behaviour of the pile is not influenced by the boundaries (Sakr and Hesham El Naggar 2003). A view of the discretized model area is given in Figure 2. The interaction behaviour between the pile and the sand soil is simulated using contact elements. The maximum shear stress in the contact area is determined by a friction coefficient. Boundary (or support) conditions for models must be specified before executing the finite element analysis. Without specifying adequate constraints the structure will be free to move as a rigid body. In the specified load transfer problem two separate boundary conditions were utilized. The nodes at the base and outer bounds of the mesh were fixed against displacement while the nodes in the symmetric plane (dividing the problem domain) were allowed to translate along the x and z axes. A total of 4484 elements, 5561 nodes were used for this analysis.

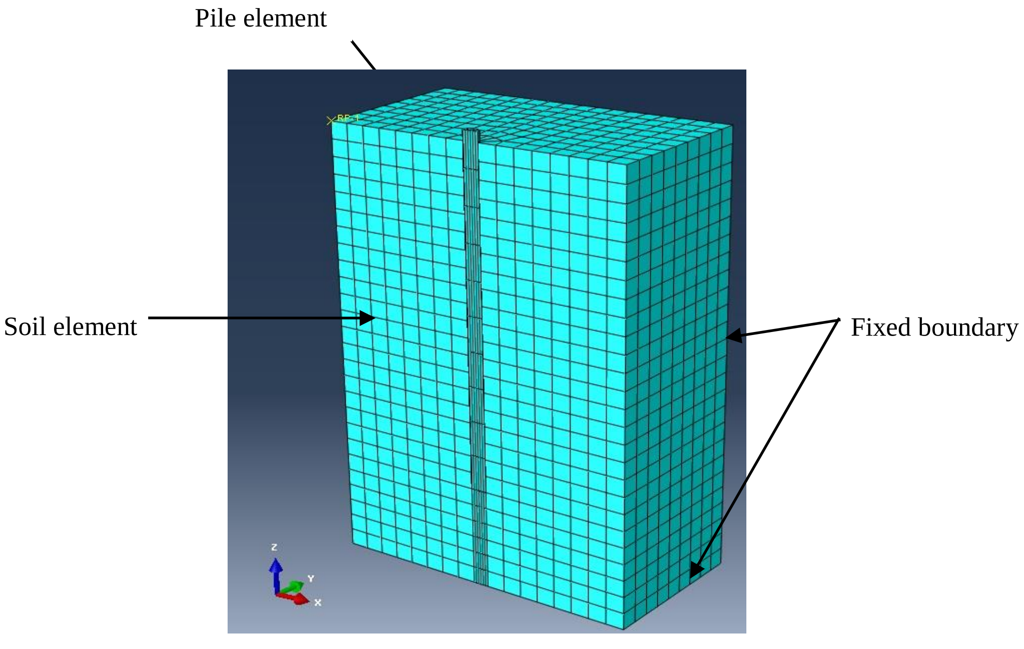

Figure 2: Axisymmetric Finite Element Model of the Pile/Soil Model

Results and discussion

A series of numerical analyses have been conducted to study the behaviour of piles under pure lateral loads and the effect of vertical load on the lateral response of piles. Several parameters were considered in this parametric study namely, (i) shear strength parameters (angle of internal friction and dilatation angle) in term of loose and dense sands (ii) pile/soil interface friction angle.

Effect of soil parameters

In the present analysis, the combine of vertical load (Py) and lateral load (Px) were applied at the head of the pile. The response of pile under combined loading was analyzed separately with different vertical load levels that equal to zero (pure lateral load), $0.25P_x$, $0.5P_x$, and $0.75P_x$ by separate numerical analyses. The combine vertical load and the horizontal load are applied simultaneously and increased gradually until the required maximum loads are reached. At the first stage, the ultimate lateral load (Px) capacity of pile model was evaluated a priori by separate numerical analyses. The ultimate lateral load of pile is obtained from load deflection curves which corresponding to a displacement of (10-20%) of the pile diameter (Chawhan et al. 2012). Figure 3 shows the pure lateral load vs. deflection relationship of pile embedded in loose and dense sand. It is noted from the figure that the horizontal deflection increases as the lateral load is increased up to about a 1200-kN pile load, at which a pile lateral displacement of about (10-20%) of the pile diameter. Shortly after that, the pile moves laterally at a greater rate, indicating that the lateral load capacity of the pile has been reached. The Figure also shows that the deflection of the pile increase at the maximum load in loose sand case compared to that obtained from the dense sand. This is expected response due to the soil in the dense case having higher stiffness than the loose sand.

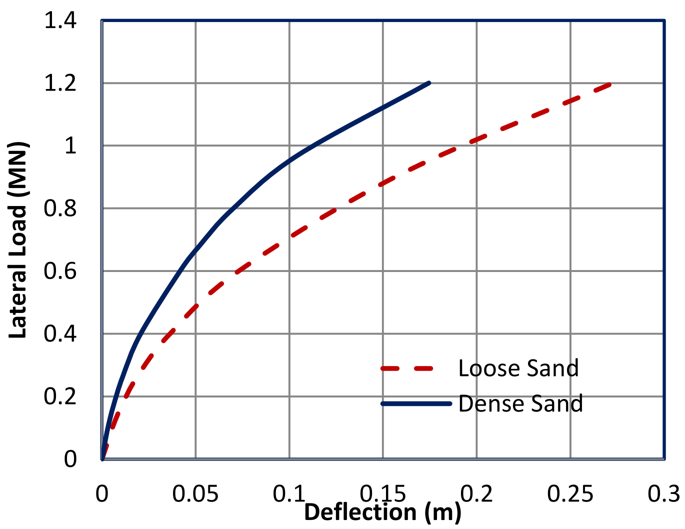

Figure 3: Load Deflection Response for Piles in Loose and Dense sand

The level of vertical load was applied first and then in the second stage, the ultimate lateral load was applied on the node corresponding to the pile head. The reaction forces developed at the nodes were used to calculate the lateral displacements corresponding to the applied lateral load (P_x). The analysis in was performed using load control (rather than displacement control) so as to know the displacement developed at various vertical load levels.

The response of piles in dense and loose sands is shown in Figures 4 and 5.It is seen from these figures that the vertical load has only a marginal influence on the lateral response of piles in the case of loose sands compared to that in dense sand. It can be noted that, in the case of dense sands, there is an increase in lateral bearing capacity with increasing vertical loads. This could be attributed to the following: (i) under the influence of vertical loads, higher vertical soil stresses develop in the soil along the pile surface leading to higher lateral stresses in the soil, (ii) higher lateral stresses in turn mobilize larger friction forces along the length of the pile. However, it is clear that the lateral soil stresses are not much affected by vertical loads in the case of loose sand as shown in Figure 5. On the other hand, the lateral stresses for dense sands increase because of the presence of vertical load as illustrated in Figure 4. The increase of lateral soil stresses leads to the development of higher lateral loads in the case of dense sands.

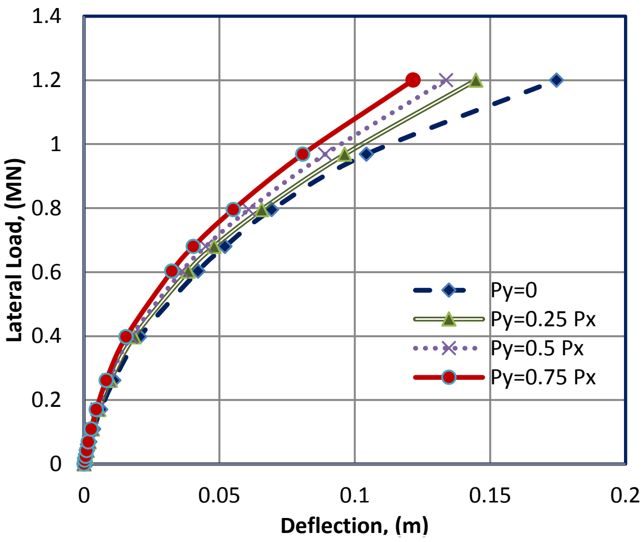

Figure 4: Lateral Load-Deflection Behaviour of a Pile in Dense Sand

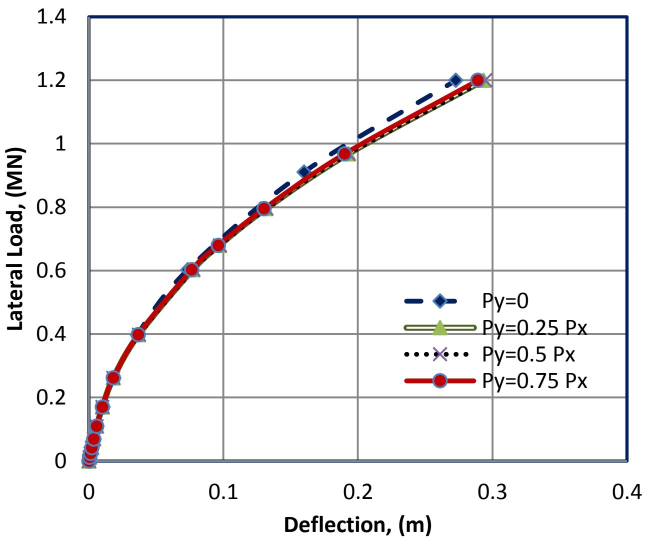

Figure 5: Lateral Load-Deflection Behaviour of a Pile in Loose Sand

This is further illustrated through lateral soil stresses developed in front of the pile at different vertical load levels for a lateral deflection, as shown in Figures 6 and 7 for loose and dense sands respectively. It is clear that the lateral soil stresses are not much affected by vertical loads in the case of loose sand as shown in Figure 6. On the other hand, the lateral stresses for dense sands increase because of the presence of vertical load as illustrated in Figure 7. The increase of lateral soil stresses leads to the development of higher lateral loads in the case of dense sands.

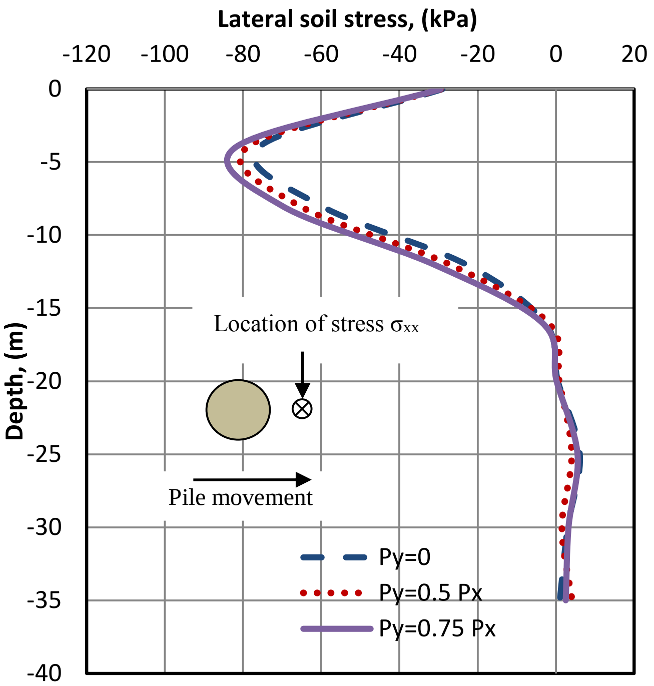

Figure 6: Variation of Lateral Soil Stress (σ_{xx}) infront of the Pile in Loose Sand

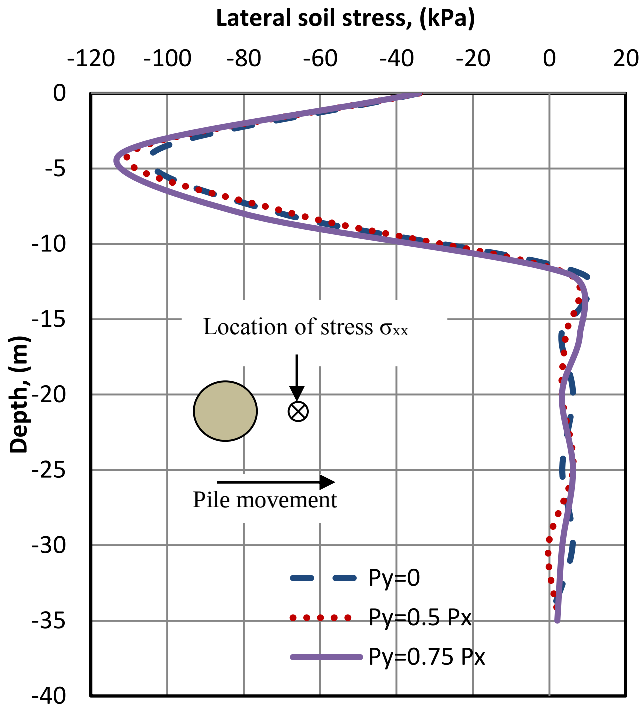

Figure 7: Variation of Lateral Soil Stress (σ_{xx}) Infront of the pile in Dense Sand

Effect of Interface Friction Coefficient

In order to verify the numerical model results with those obtained from experimental model, the FRP pile/sand model was simulated using the contact property technique in term of interface friction. The interaction relationship between pile and soil around and bottom pile can simulate the penalty contact-type (Pan et al. 2011). This type of interface friction is capable of simulating the interface friction between the pile surface and the soil in contact (Sam 2007). The external surface of the pile and pile tip are contacted with the soil as shown in Figure 8. The ABAQUS interface modelling technique is used to simulate slip at the soil/pile interface (ABAQUS 2010). ABAQUS uses the Coulomb frictional law in which frictional behaviour is specified by an interface friction coefficient, μ.

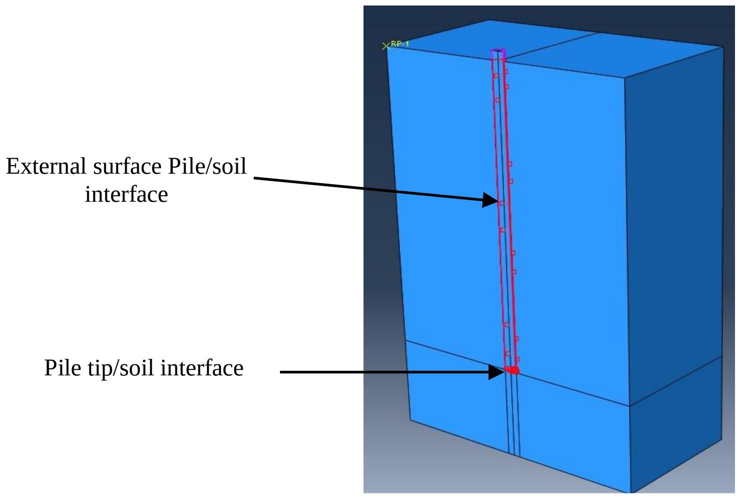

Figure 8: The Interface Friction Elements

As the previous results have clearly shown that the influence of vertical load is more prominent in the case of dense sands, the influence of interface friction coefficient was study only for the (P_y=0.5P_x). To investigate the effect of interface friction coefficient, a three FE analyses were conducted for both soil state (loose and dense). These analyses were conducted using three different interface friction coefficients (0.22, 0.32, and 0.42) respectively. The comparison, in term of the pile load deflection was presented in Figure 9. As a result it can be seen that that both cases behaved in a similar manner between three analyses. It is clear that the coefficient of interface friction vertical loads have very little influence on the lateral deformations during the applied vertical load on both loose and dense sand.

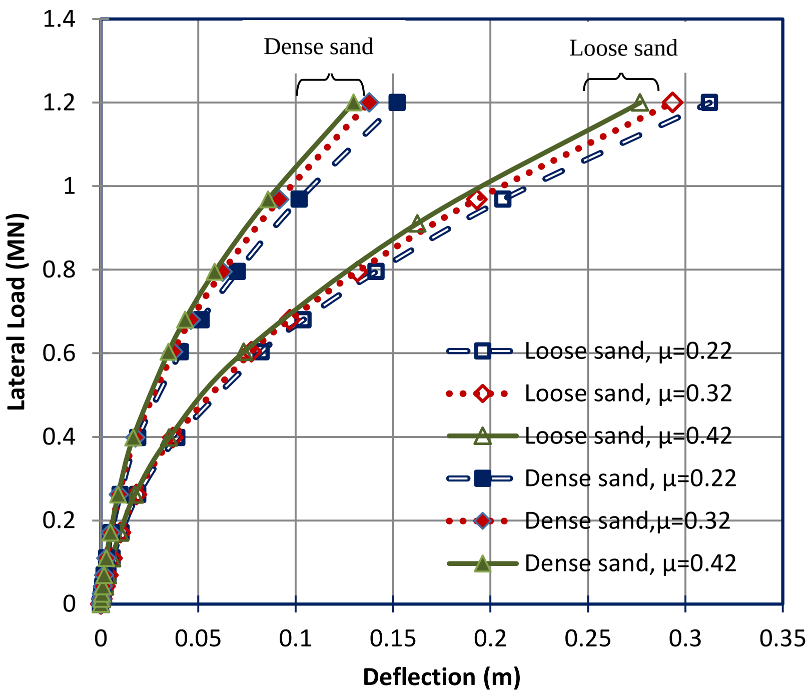

Figure 9: Effect of Interface Friction Coefficient on Lateral Load-Deflection Response Pile in Dense and Loose Sands

Conclusions

The behaviour of single pile subjected to combined vertical and lateral loads has been investigated in this study through a serious of three-dimensional analysis using Abaqus software. The single pile under combined loading was analyzed separately with different vertical load levels that equal to zero (pure lateral load), 0.25P_x, 0.5P_x, and 0.75P_x by separate numerical analyses The influences of related parameters such as shear strength (angle of internal friction and dilatation angle) of soil in term of loose and dense sands cases and pile/soil interface friction coefficient. The results show that the behaviour of pile under combination of vertical and lateral loads has larger resistance to lateral load as compared to pile under pure lateral load only for the case in dense sand. The reason could be directly attributed to the development of additional lateral soil stresses in front of the pile and additional frictional resistance developed along its length. The coefficient of interface friction between the pile and sand has a minor effect on the pile response when subjected to lateral load during the applied vertical load in both loose and dense sand cases.

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