DYNAMIC ANALYSIS OF PILES IN SAND BASED ON SOIL-PILE INTERACTION

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ABSTRACT:

Seismic soil-pile-structure interaction is a complex phenomenon that can affect the response of structures significantly during earthquake. Considering complexities which exist in soil-pile-structure interaction problems and the lack of theoretical bases, it is necessary to use numerical methods for analyzing soil-pile-structure interaction problems.

In this research program, a three dimensional modeling procedure is carried out to study the behavior of piles under earthquake loading. Dynamic analyses were carried out on the model containing the pile and its surrounding sand. To verify the model, analyses are performed using harmonic excitation. Dynamic analyses are also carried out with KOBE earthquake record applied at the bedrock level as acceleration time histories. In all analyses it is assumed that bedrock is at the bottom of the model. The soil is modeled as an elastoplastic material using the Mohr-Coulomb failure criteria. Contact elements are used at soil-pile interface to model the gap behind the pile and the compression in front of it. The side boundaries are constrained against horizontal direction and the bottom boundaries are constrained against both horizontal and vertical directions. In addition quiet boundaries are used to eliminate the "box effect" (i.e., the reflection of waves back into the model at the boundaries). The F.E. software ABAQUS, is used for all analyses in this research program. A sensitivity analysis is performed to study the effect of sandy soil parameters on the lateral seismic behavior of pile. Bending moment and shear force diagrams together with predicted deflections along the pile are also presented in this study.

KEYWORDS: Soil-pile interaction, Dynamic lateral loading, Numerical modeling, Sand

1. INTRODUCTION

Many studies have been devoted to lateral response of single piles. Various approaches have been developed for the static and dynamic lateral response of piles such as boundary element analysis, e.g. Banerjee [1] and Kaynia and Kausel [2], but the inclusion of soil nonlinear behavior in this approach is difficult. Nogami and Konagai [3, 4] analyzed the dynamic response of pile foundations in the time domain using a Winkler approach. El Naggar and Novak [5, 6] presented a nonlinear analysis for pile groups in the time domain within the framework of the Winkler hypothesis. However, proper representation of damping and inertia effects of continuous soil media is difficult with such discrete systems. Using the Drucker-Prager soil model with finite element technique, Maheshwari et al. [7] considered the plasticity of soil when analyzing the kinematic response of single piles.

In the current study, three dimensional nonlinear dynamic sensitivity analyses were performed to investigate the effect of changing soil parameters on the seismic lateral behavior of the pile. These analyses accounted for soil-pile interaction, soil-pile gapping and slippage, soil plasticity and 3D wave propagation.

2. MODELING THE SOIL-PILE SYSTEM

In this section, the 3D mesh, boundary conditions and properties of soil and pile will be discussed. The material properties are the same as Maheshwari et al. [7].

2.1. Finite Element Model

A three-dimensional geometric model was used to represent the soil-pile system. Soil and pile were modeled using eight-node block elements. The vertical Z direction subdivisions were kept constant to allow for an even distribution of vertically propagation SH waves; that is, pile and soil model was divided by elements having equal vertical dimensions, while horizontal dimensions of soil elements are gradually increased moving toward the boundaries of the model. In fact, the mesh was refined near the pile to account for severe stress gradients in the soil with a gradual transition to a coarser mesh away from the pile in the horizontal directions as shown in figure 1.

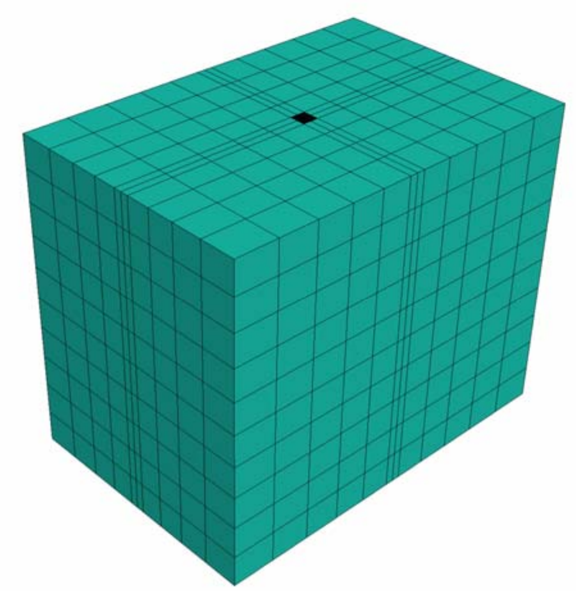

Figure 1 Three-dimensional finite element model used for the soil-pile system

The numerical mesh has a width of 8 m and length of 12 m with the height of 10 m. The size of elements in the horizontal plane varies from 0.25 m to 2 m and each element has height of 1 m.

The surface to surface contact method was used at soil-pile interface to allow for separation in tension behind the pile and ensured compatibility in compression in front of it. These surfaces are called master-slave surfaces and contact pair. This is well discussed din ABAQUS manual [8].

2.2. Boundary Conditions

The pile is completely embedded in the soil and it is assumed to be bearing on the bedrock. Therefore all the bearing nodes are taken as fixed. It is assumed that the soil and pile are perfectly bonded. The side boundaries are constrained against horizontal direction and the bottom boundaries are constrained against both horizontal and vertical directions. Also, quiet boundaries are used for wave propagation and to eliminate "box effect" (i.e., the reflection of waves back into the model at the boundaries). To apply the quiet boundaries to the model, infinite elements are used at the boundaries.

2.3. Model Parameters

According to Maheshwari et al. [7], the Drucker-Prager failure criteria are used in the verification section to model the clayey soil medium. The material properties of clayey soil are as follows: elastic modulus (E) =20 MPa, soil unit weight (γ) =11.8 kN/m^3, Poisson's ratio (ν) =0.45, cohesion (c) =34 kPa, friction angle (φ) =16.5^o, dilation angle (ψ) =16.5^o, shear wave velocity (V) =60-120 m/s and coefficient of earth pressure at rest (K_0) =0.65. In dynamic analyses, the sandy soil is modeled as an elastoplasic material using the Mohr-Coulomb failure criteria. The material properties of sandy soil are as follows: E=30 MPa, γ_d=16 kN/m^3, ν=0.35, c=0 kPa, φ=28^o, ψ=16.5^o and K_0=0.45.

In both verification and dynamic analyses, Rayleigh damping is used to model the damping in the system. Rayleigh damping consists of mass and stiffness parts and is given by Eqn. 2.3.1.

$$C = \alpha M + \beta K \tag{2.3.1}$$

Where α and β are constants, M is the matrix of mass and K is the matrix of stiffness. To evaluate α and β parameters, some modal analyses were performed to obtain the natural frequencies of the soil-pile system. Critical damping coefficient of the soil is assumed to be equal to 5%.

It is assumed that the pile is made of concrete and has a square cross section with each side equal to 0.5 m. The length of the pile is 10 m and it is modeled as an elastic material using Elastic model with the following properties: E=20000 MPa, γ=23 kN/m^3, ν=0.3 and moment of inertia (I) =5.208×10^{-3} m^4.

3. DYNAMIC LOADING

Seismic loading is applied at the bedrock level in the horizontal direction as acceleration time history. In the verification section, harmonic excitation consists of a sinusoidal wave of unit amplitude and different frequencies, while in the final dynamic analyses, the first 7.94 seconds of KOBE earthquake record were used.

4. VERIFICATION FOR DYNAMIC LOADING

Verification is accomplished for free-field and pile-head cases. In both cases, the amplitude of steady-state response is noted and normalized with respect to the amplitude of input bedrock motion. Thus, normalized amplification to soil stratum is derived at different frequencies and compared with Maheshwari et al. [7] results as shown in figures 2 and 3. From figures 2 and 3, it can be observed that the response obtained from the 3D model analysis is in good agreement with Maheshwari et al. [7] results at lower frequencies (i.e., dimensionless frequency (a_0)<0.5), while at higher frequencies Maheshwari et al. [7] results are smaller than the response obtained from 3D model. This may be attributed to the differences assumed for boundary conditions in the presented study and Maheshwari et al. [7] study. In the model studied by Maheshwari et al. [7], Kelvin elements were used at the boundaries while in the present model quiet boundaries and infinite elements were applied to the boundaries. At the frequencies lower than 0.6, pile-head response is higher than free-field response. It may be attributed to stiffness variations of the system due to adding the pile into the soil medium.

5. SENSIVITY ANALYSES

In this section, the goal is to study the effect of changing soil parameters on the lateral seismic behavior of pile. Shear forces, bending moments and deflections of the pile due to variations in sand density, friction angle and Poisson's ratio were predicted.

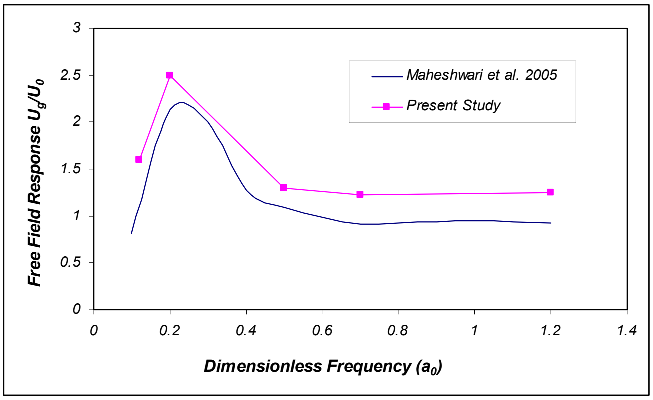

Figure 2 Dynamic verification for free-field response

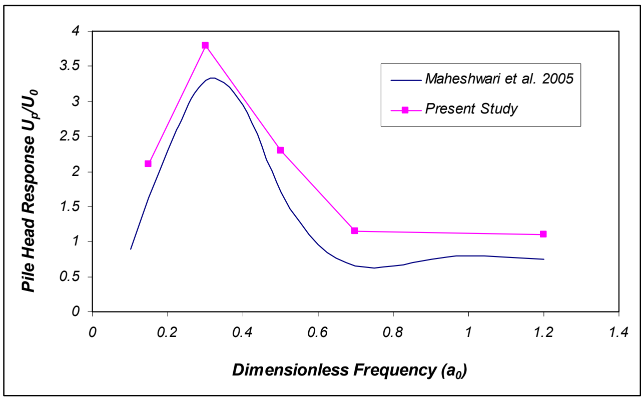

Figure 3 Dynamic verification for pile-head response

5.1. Effect of Sand Density

Figure 4 shows that maximum deflection of the pile occurs at the bottom of the pile and is almost constant against the sand density variations.

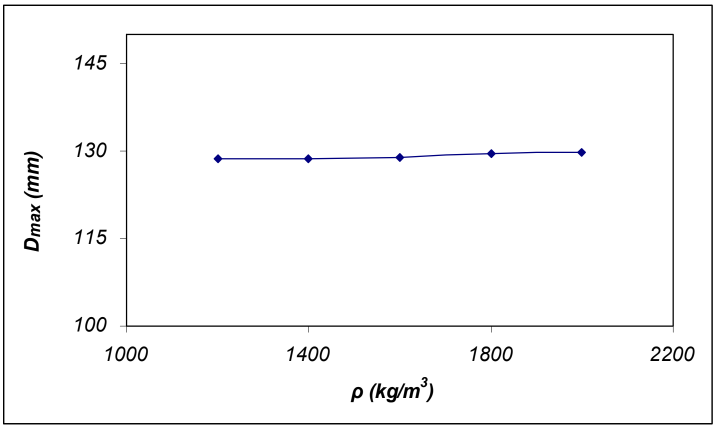

Figure 4 Maximum pile deflections versus sand density

It can be observed from figure 5 that the maximum shear force in the middle and bottom of the pile decreases slightly as sand density increases. Figure 5 also shows that the maximum shear force for all densities occurs at depth of 10 m.

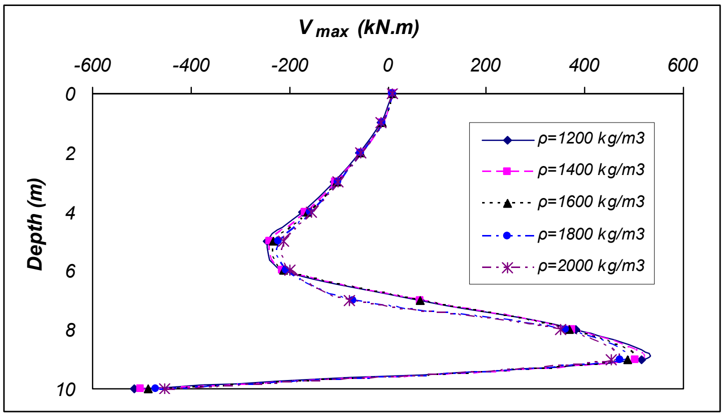

Figure 5 Maximum shear forces in the versus sand density

In figure 6 maximum bending moments in the pile are shown for different sand densities. Same as shear force, the maximum bending moment decreases in the middle of the pile due to increase in sand density.

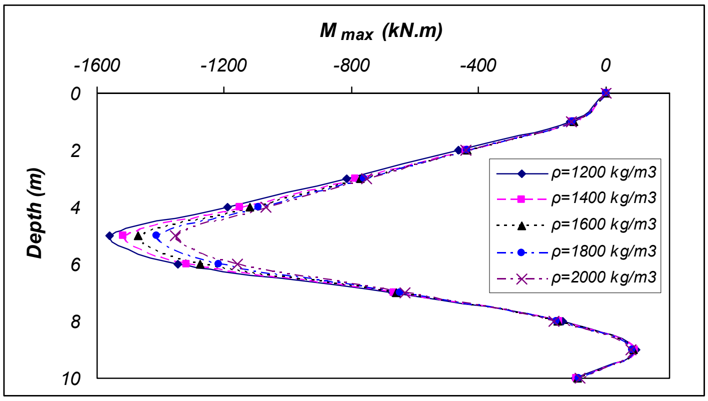

Figure 6 Maximum bending moments in the pile versus sand density

5.2. Effect of Sand Friction Angle

It can be observed from figure 7 that the maximum pile deflection at the bottom of the pile gradually decreases if sand friction angle increases.

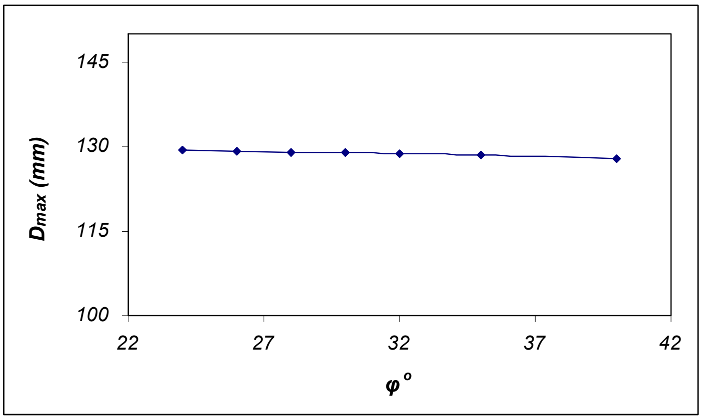

Figure 7 Maximum pile deflections versus sand friction angle

Figure 8 shows that the maximum shear force in the middle and bottom of the pile decreases about 80 kN by increasing the sand friction angle from 24° to 40°. Both sand density and sand friction angle have the same effect on the behavior of the pile.

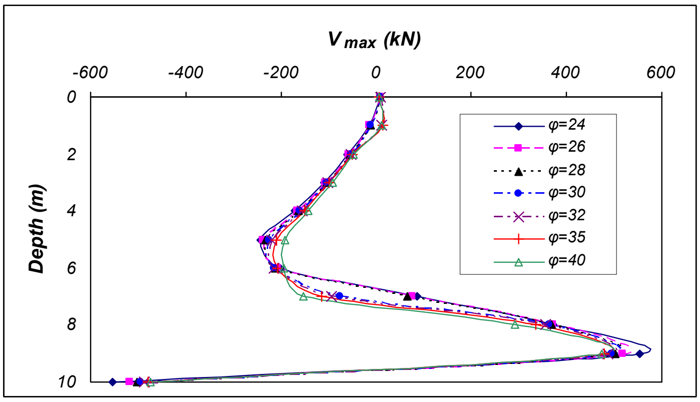

Figure 8 Maximum shear forces in the pile versus sand friction angle

According to figure 9, the maximum bending moment decreases in the middle of the pile due to increase in sand friction angle. The inverse effect of this parameter on the pile behavior may be attributed to the increase in sand stiffness; that is, by increasing the sand friction angle, loose sand changes to dense sand. Thus, with an increase in sand friction angle, the forces applied to the pile decrease. This is similar to the response of piles when the soil elastic modulus increases.

Also, the negligible effect of this parameter on the pile behavior may be attributed to remaining the soil in elastic zone. Figure 10 illustrates the plastic strains in the sand in the last second of earthquake loading with friction angle equal to 40°. According to this figure, for all 7.94 seconds of loading the sand behaves elastically. Therefore, variation of this parameter of the sand does not make any significant difference in the pile behavior.

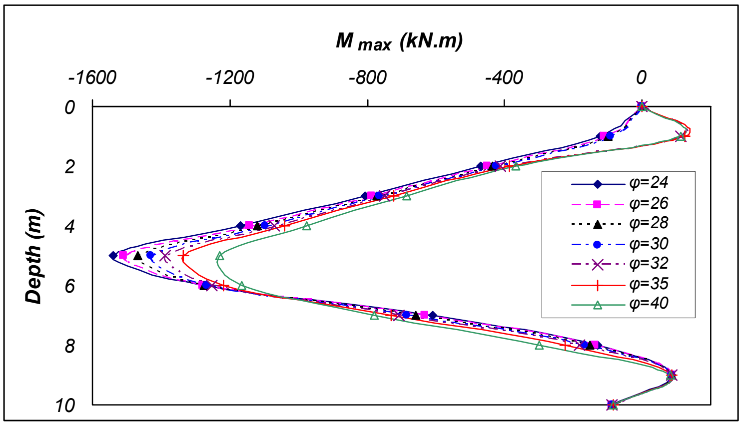

Figure 9 Maximum bending moments in the pile versus sand friction angle

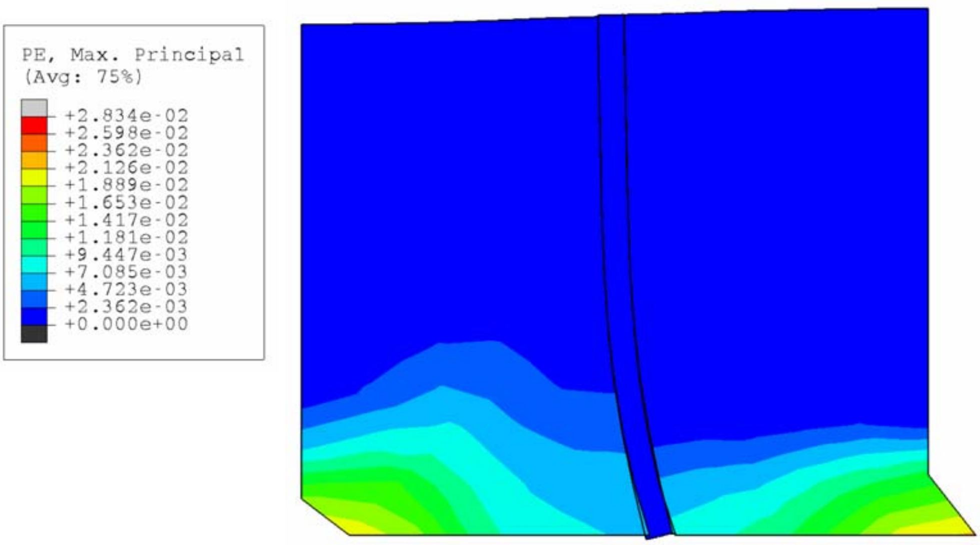

Figure 10 Plastic strains near the pile (φ= 40°)

5.3. Effect of Sand Poisson's Ratio

Figure 11 shows that by changing the Poisson's ratio, the maximum pile deflection is nearly constant and it increases about 4 mm.

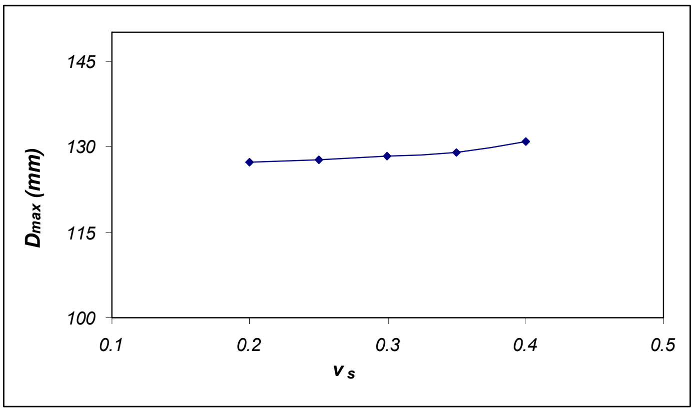

Figure 11 Maximum pile deflections versus sand Poisson's ratios

From figure 12 it can be observed that by increasing the sand Poisson's ratio the maximum shear force in the pile remains nearly constant.

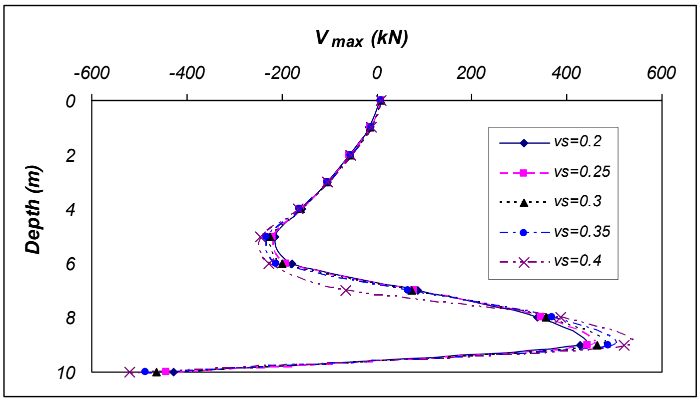

Figure 12 Maximum shear forces in the pile versus sand Poisson's ratios

According to figure 13, the maximum bending moment in the pile changes only in the middle of the pile and all other points are nearly constant. The increment of bending moment in the middle of the pile is about 155 kN.m and in comparison with the bending moment at this point, which is about 1350 kN.m, the difference in the bending moment is negligible.

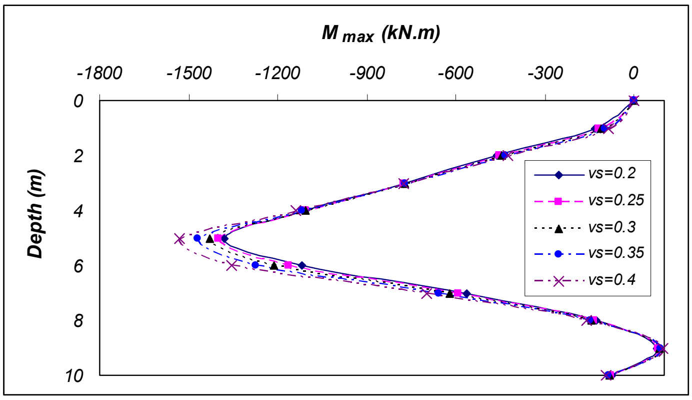

Figure 13 Maximum bending moments in the pile versus sand Poisson's ratios

6. CONCLUSION

The increment in both sand density and friction angle results in smaller values for maximum bending moments and shear forces, while by increasing the sand density and friction angle, the pile deflection remains nearly constant. Also in this study it is observed that sand Poisson's ratio does not have any considerable effect on pile forces and by increasing the sand Poisson's ratio no significant change in the maximum bending moment, shear force and deflection of the pile is predicted.

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