DYNAMIC RESPONSE OF A PILE RESTING ON SLOPING GROUND UNDER DIFFERENT EARTHQUAKE MOTIONS

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Abstract

Pile foundations are often used on sloping ground to support large vertical as well as lateral loads coming from various structures such as high-raised buildings, bridge abutments and transmission towers. The phenomenon of soil-structure interaction is a complex process, and it becomes more complicated under earthquake loading. Major portion of northern and north-east India is covered with hill slopes, which are also seismically very active. This study aimed to understand the behavior of a single pile resting near the crest of cohesionless soil slopes under dynamic loading conditions. The dynamic response of the pile is determined by performing a series of numerical simulations using three-dimensional finite element analysis. In this study, the pile was modelled using linear elastic material, whereas surrounding cohesionless soil is modelled using mohr-coulomb yield criteria. Numerical analysis is carried in two phases: (i) Assessment of Initial stresses generated by gravity loading using appropriate boundary conditions, and (ii) Assessment of dynamic stresses induced under different earthquake base motions. Numerical simulations were carried for both level and sloping ground under three different earthquake scenarios (i.e. spectrum compatible motions). Acceleration time histories are measured at different points along the pile and surrounding soil to understand behavior of pile on sloping ground with respect to level ground and also to evaluate the effect of different earthquake motions. From time history plots, it is observed that motion at the top surface of slope is amplified compared to the base input motion. The load-carrying capacity of a pile decreases with the increase in slope angle due to the reduction in passive resistance of the soil. From the results, it is also observed that the pile top is more susceptible to damage compared to the bottom of the pile under the action of dynamic loads.

Keywords: Dynamic Response of a Pile; Cohesionless Soil; Sloping Ground; Earthquake Loading; Finite Element Analysis;

1. Introduction

Recently, the occurrence of earthquakes around the world has been significantly increased, and at the same time, the urbanization in cities and rural areas are also increased. Due to this rapid urbanization, the availability of the flat grounds and good quality lands for the construction of structures has been decreased. So, the construction on the man-made slope and/or natural hilly areas has been increased in last few decades. Pile foundations are one of the most suitable type of foundations for these types of locations and also for earthquake loading conditions. The behavior of pile foundations during earthquakes are strongly affected by the non-linear response of pile-soil interaction. The collapse of pile foundations supporting intact/undamaged superstructures during earthquakes near sloping grounds is one of the major problem to the geotechnical engineers. The response of pile-soil interaction on sloping ground is a complicated phenomenon and it becomes more complex when an earthquake scenario is considered. Considering the difficulties which exist in soil-pile interaction problems under earthquake scenario, it is essential to use numerical simulations for analyzing these interaction problems [1].

An extensive research has been carried on single pile and pile groups located in level and sloping grounds of saturated cohesionless soil under dynamic loading conditions (i.e., liquefaction and lateral spreading). As compared to the saturated cohesionless, a few studies has been carried on dynamic behavior of single piles resting in dry cohesionless soil slopes. Muthukkumaran and Subha [2, 3] studied the dynamic behavior of single pile in a sloping ground under earthquake induced lateral soil movements. The effect of length to diameter of pile on lateral displacement and bending moment studied for constant slope inclination and steady depth of liquefiable layer. Deendayal et al. [4] studied the response of a solid concrete piles resting on clayey soil underlain by sandy soil subjected to both static vertical load as well as dynamic loads (earthquake motion) using the finite element method software Plaxis 2D. From results, the amplification of ground motion and deformation of pile behavior has been studied. Deendayal [5] performed numerical analysis using two-dimensional finite element method to understand the dynamic response of a pile resting on layered soils by varying slope inclinations and length to diameter ratio of the pile. From results, it is concluded that the bending moment, maximum displacement and the acceleration decreases with increase in the length to diameter ratio of the pile.

From above literature, it can be seen that most of the studies were carried out on single piles resting on level ground under dynamic condition. Very few researchers have studied the behavior of single piles located on cohesionless using numerical studies. However, these studies are not sufficient to understand the dynamic behavior of piles in sloping ground. Therefore, it is necessary to study the performance of a single pile under dynamic conditions. The main aim of this paper is to study the response of a single pile located at the crest of dry cohesionless soil slope under different earthquake time histories. This objective is achieved by performing a series of numerical simulations using a three-dimensional finite element software, Plaxis 3D.

2. Methodology

Plaxis 3D, a general purpose geotechnical finite element method software was used to perform the numerical simulations of a single pile resting on cohesionless soil slope under seismic loading conditions. A loose to medium dense soil layer of depth 30m was considered for the analysis and schematic diagram of site/problem is shown in Figure 1. As shown in the figure, a soil slope inclination of 20^0 was modeled and a single solid concrete pile was made at the edge of the slope crest. Dynamic interaction between pile and surrounding soil was considered by providing an interface of virtual thickness of 1cm. Stress-strain behavior of a soil was modeled using Mohr-Coulomb Yield Criteria (linear elasto-plastic model), whereas concrete pile was modeled using Hooke's law (linear elastic model). For solid pile, M25 grade concrete was considered for simulations (minimum grade for pile as per IS 2911). Properties of pile and the surrounding soil used in the analysis are shown in Table 1. Properties of the virtual interface has been provided same as that of surrounding soil with reduced shear strength properties using a strength reduction factor. Static loading was applied at the center of pile top in the direction of soil slope in terms of prescribed displacement.

In dynamic finite element analysis, element size plays a crucial role in the propagation of high frequency waves. Average element size of the pile and soil domain is maintained less than ---. A ten noded tetrahedral elements were used to represent the both soil and pile, and a twelve noded interface element is used to simulate the virtual interface between the soil and the pile.

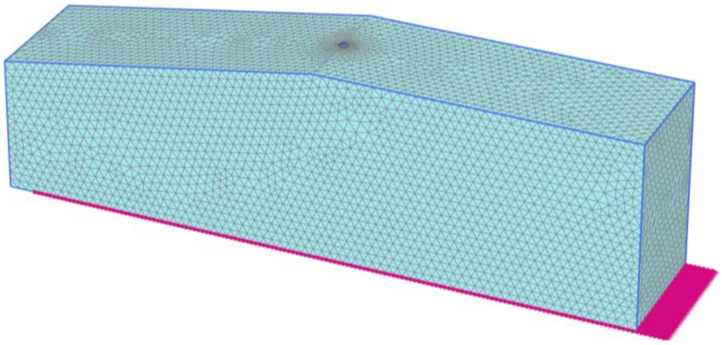

Fig. 1 – Finite element model of a single pile resting on cohesionless soil slope

Table 1 – Properties of surrounding soil and solid pile used in the simulation

Material\Properties	γ (kN/m^3)	φ (^{0})	E (MPa)	υ	Rayleigh Damping	
					α	β
Sandy Soil	17	30	30	0.30	0.385	0.00234
Concrete Pile	24	-	25e3	0.15	0.385	0.00234

Boundary also plays a vital role in the numerical simulations. So, different boundary conditions have been considered for different loading cases (i.e., static and dynamic). In static loading case, all the vertical sides of the model were considered to the normally fixed in horizontal direction and bottom of the model was considered completely fixed in all the directions. In dynamic loading case, material damping and radiation damping plays a significant role in absorption and reflection of waves through and at the end of the soil model. Material damping in analysis was considered in terms of Rayleigh damping coefficients (i.e., α and β). These coefficients are mainly dependent critical damping ratio and natural frequencies of the soil. Radiation damping was applied by providing viscous dampers at the boundaries of the model.

In this study, soil site is assumed to be located in the seismic zone IV as per IS 1893 Part I. SeismoMatch software has been used to generate spectrum compatible motion corresponding to the particular seismic site. For this purpose, different previous natural earthquake time histories (i.e., Kocaeli Earthquake, ChiChi Earthquake, and Denali Earthquake) have been considered. The IS 1893 response spectrum has been used as targeted spectrum and matched with these time histories to generate spectrum compatible motion. These spectrum compatible time histories are free field motions. To get bed rock motions, the free field motions are deconvoluted using 1-D ground response analysis software, DEEPSOIL. These deconvoluted spectrum compatible time histories have been used as bed rock motions and applied at the bottom of the model.

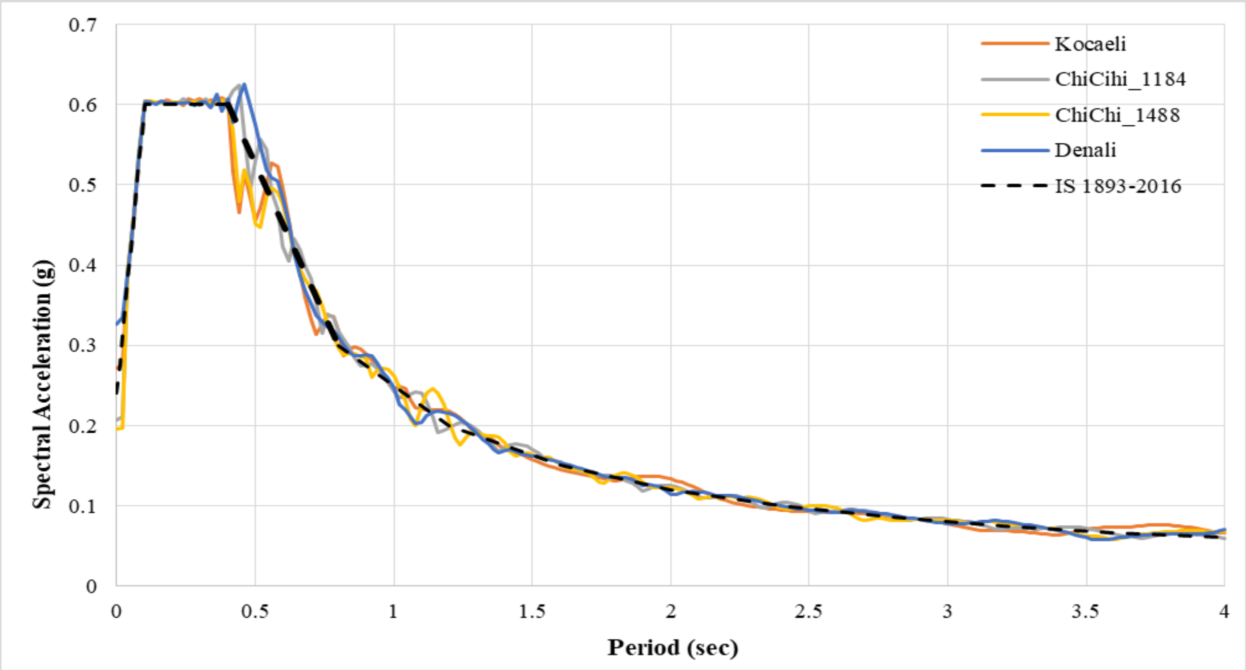

Fig. 2 – Matched response spectrums of different natural time histories compatible with IS Code spectrum

Numerical analysis has been carried out in the following three stages. In first stage, only soil elements have been activated and initial soil stresses calculated using gravity procedure. In second stage, pile elements and static loads has been activated. Plastic procedure has been used for calculating stresses and displacements in stage using static boundary conditions. In final stage, earthquake time history applied at the bottom of the model has been activated. Dynamic procedure has been used for calculating stresses, displacements, and accelerations in stage using viscous boundary conditions. Results from the numerical analyses were further analyzed to study the influence of each parameter on dynamic pile-soil interaction, which is clearly discussed in the following section.

3. Results and Discussions

Numerical simulations has been carried out using Plaxis 3D to understand the dynamic response of a single pile located at the crest of the dry cohesionless soil under different spectrum compatible earthquake motions. Analysis has been carried out on both level ground and sloping ground to under the pile-soil slope interaction under earthquake condition. From the analysis, results were extracted at selected locations and discussed in terms of acceleration time histories and deformation profiles along the depth of pile.

Figure 3 shows the variation of acceleration time histories at different points along pile depth for Kocaeli Earthquake, when a single pile is located at the crest of dry cohesionless soil of 10 degrees. It can be seen that the acceleration was amplified from the middle of the pile to the top of the pile. This behavior was observed due to the increase stiffness of long flexible pile. Same behavior has been in the other time histories with different amplifications along the pile depth.

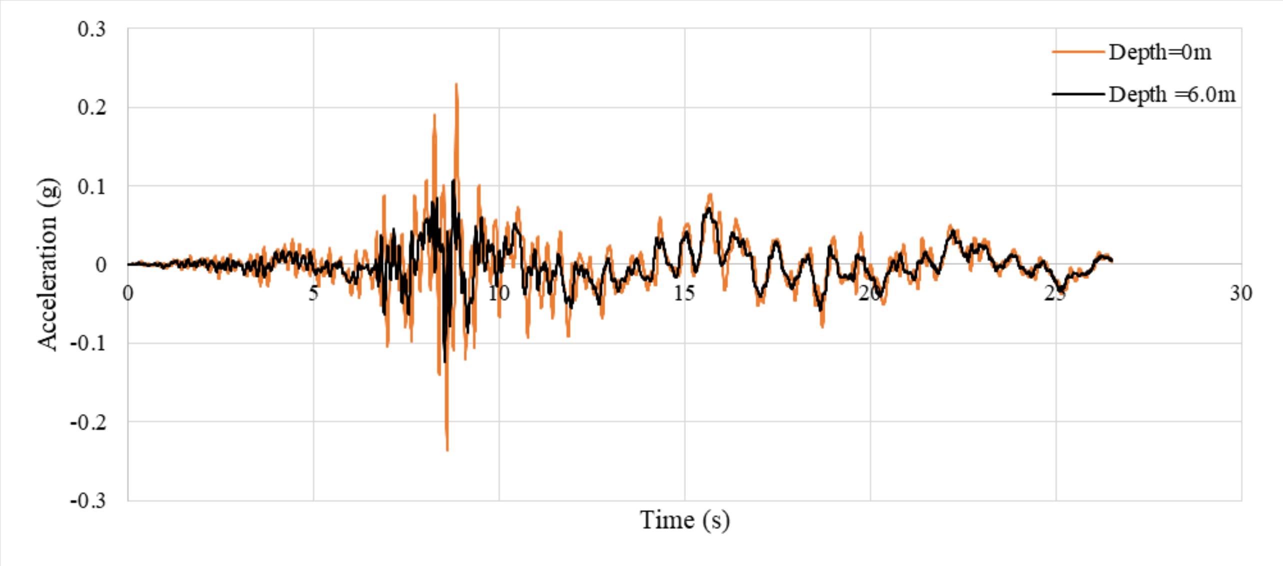

Fig. 3 – Acceleration time histories at top and middle of the pile located in cohesionless soils

The variation of lateral force and displacement at the top of the pile having a diameter of 0.6m are shown in Figure 4 & 5. From figure, it can be observed that the lateral load carrying capacity and displacement at the top of the pile reaches a maximum value of 6E4 kN and 0.33m, respectively. The cross-section of displacement contour at the middle of the pile-soil slope configuration was shown in Figure 5.

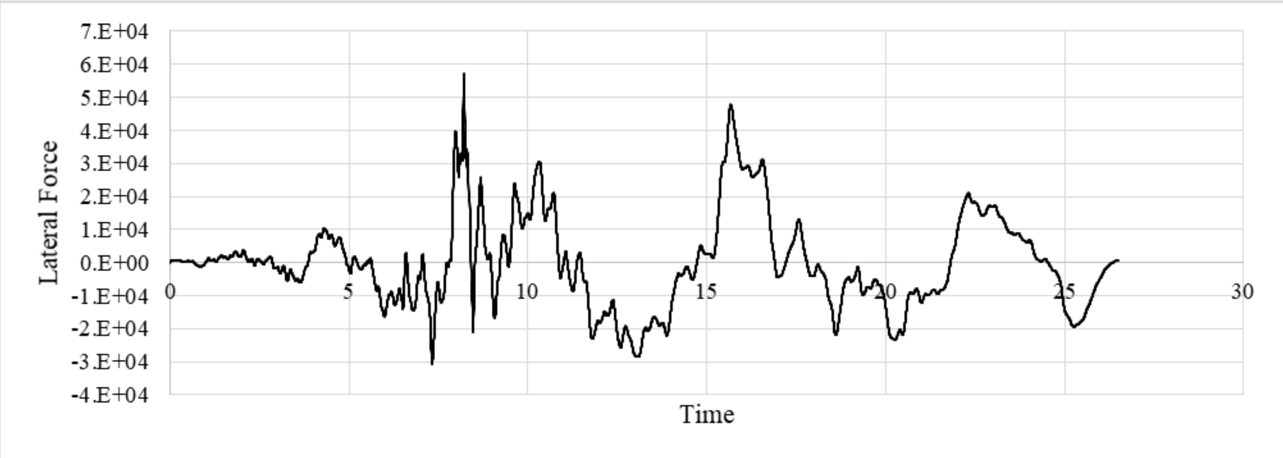

Fig. 4 – Lateral force vs time curve of a single long pile resting on cohesionless soils

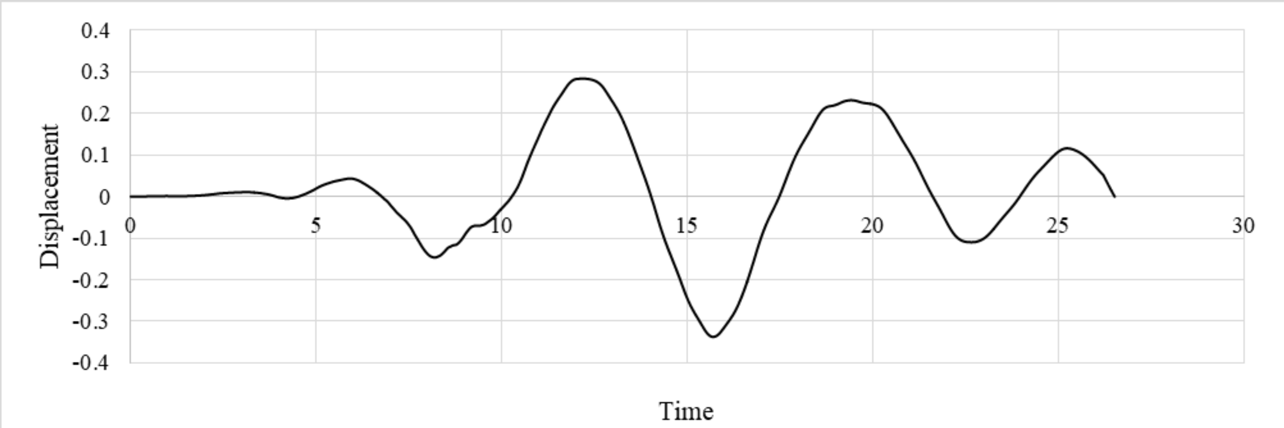

Fig. 5 – Lateral displacement vs time curves at top of the pile located in cohesionless soils

4. Conclusions

In this numerical study, a three-dimensional dynamic finite element method has been used to study the non-linear response of pile soil interaction under dynamic loading conditions using different natural spectrum compatible earthquake motions. The following conclusions have drawn from the numerical simulations: From different spectrum compatible time history plots, it was observed that motion at the free surface of soil slope amplified compared to the base input motion and similarly the motion along pile depth was also amplified. The load-carrying capacity of a pile in sloping ground decreases as compared to level ground due to the reduction in passive resistance of the soil. From the results, it is also observed that displacement at the pile top varies with time histories considered in the analysis.

6. References

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