The Seismic Evaluation of Pile Behaviour in Liquefiable and Non-liquefiable Soil

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Abstract

Pile foundation technique is developed to support structures and buildings on soft soil. The most important dynamic load that can affect the pile structure is earthquake excitation. From the 1960s the comprehensive investigation of pile foundation during earthquake excitation indicates that piles are subject to damage by affecting the superstructure integrity and serviceability. The main part of recent researches have been focused on the behavior of liquefiable soil and lateral spreading load on the piles. According to this investigation, the damage is between the liquefiable and non-liquefiable layers. This damage can crush the pile head by increasing the inertial load which is applied by the superstructure. The cracks on the piles due to the surrounding soil directly relate to the soil profile. Designing of the pile is always a challenge in liquefaction soil due to two distinct criteria; one elastic response of pile and the maximum allowing deflection at the top of pile. Moreover, the absence of plastic hinges in the pile should be insured, because the damage in the pile is not observed directly. In this study, the shear forces/displacement and the bending moment of the pile in the liquefiable and non-liquefiable layers are investigated during a time history analysis. The OpenSeesPL software has been used to model the piles. The results show that the earthquake magnitude and soil properties can effectively change the total behavior of the piles.

Keywords: Pile, Earthquake, Liquefaction, Non-Liquefiable, Shear Force, bending moment.

Introduction

Pile foundations are very vulnerable during earthquake excitation in different soil layers and the surrounding soil has a direct influence on piles behavior. Soils with different stiffness have different behavior during earthquake and casus drastic deformation and stress through the pile length (Bobet, Salgado, & Loukidis, 2001).

During an earthquake, two types of stresses can damage the pile's head; inertial load that is caused by superstructure and deformation, which caused by the surrounding soil. Soil deformation and inertial load are associated with the earthquake's acceleration. The acceleration amplitude at the ground surface depends on the magnitude of earthquakes, soil properties, and seismic source distance.

The previous observations on the piles performance in liquefied layers showed that the negative effect of liquefaction has rang from structural damage to excessive deformations. Predicting the piles behavior in liquefiable soil that subjected to earthquake excitation is very complex, which needs to consider the inertial and kinematic loads (Wilson, Boulanger, & Kutter, 2000). The liquefaction phenomenon is one of the important problems during earthquake excitation. Geotechnical engineers have mentioned that the same soil with different degree of saturation presents different performance during earthquake. Generally, liquefaction occurs in saturated sand when the pores are completely filled with water. The water in the pores applies the pressure on the sand particles that named pore pressure and represents how the soil particles are pressed together (Youd, 1990). Before an earthquake, the pore pressure is low and the earthquake excitation increases the pore pressure. The sand particles start to move freely without any shear strength between particles. Therefore, soils typically comprising three parts, solid soil particles, water, and air. The degree of saturation is used to specify the relative amount of water contained in the voids.

By focusing on the effect of degree of saturation on the properties of sand, some researchers revealed that full saturated sand or even near to full saturation condition can cause a substantial variation in the liquefaction resistance of sand (Xia & Hu, 1991). Ports, wharves and bridges are always susceptible to liquefaction. Such damage can have extreme consequences in terms of either human life or economic loss (Abdoun, Dobry, & O'Rourke, 1997). In this study, the performance and behavior of pile foundation during three different layers are investigated. A liquefaction sand layer placed between two non-liquefiable clay layers with different stiffness. And the time history analysis of the pile revealed the behavior of the pile during three earthquake around the word with same soil properties that represent the soil's characteristics of earthquake regions. The pile has been modeled by OpenSeesPL software and the variation of shear force and bending moment for each earthquake in each layer have been discussed.

Liquefaction Effect

The liquefaction cannot be damaging by itself, only with seismic excitation, it will change the soil structure and destruction appears. Moreover, liquefaction has different forms such as lateral spreading, flow failure, loss of bearing strength, ground oscillation and settlement (Abe & Kuwabara, 2004). The stiffness reduction is one of the detrimental consequence of liquefaction (Arab, Shahrour, & Lancelot, 2011). The piles reaction in stiffness reduction in most cases leading to diagonal cracks at the pile head (Bobet et al., 2001).

There are two parameters which control lateral load in the liquefied soil; ultimate pressure and stiffness reduction factor (Kutter & Voss, 1995). To evaluate the ultimate pressure, the residual strength of liquefied soils will lead to the correct direction (Ashford, Boulanger, & Brandenberg, 2011). There are some elements that stiffness reduction factor is affected by them such as pore pressure, ground displacement, sand density, and drainage condition (Tokida, Matsumoto, & Iwasaki, 1992). Normally, the value of stiffness reduction factor for cyclic liquefaction is between 1/50 and 1/10 and for lateral spreading is between 1/1000 and 1/50 (Xia & Hu, 1991).

In fact, the stiffness reduction factor has a close relation to the soil properties and ground deformation (Youd & Hoose, 1978). The lower value of this factor has shown the loose property of soil (Cubrinovski, Ishihara, & Poulos, 2006). The evaluation of liquefaction consists of the following steps:

- investigation of soil property
- assessment of the susceptibility for liquefaction in soils
- evaluation of instability of the slopes due to liquefaction or estimation of expected vertical and lateral displacements (Martinelli & Tamagnini, 2013)

Ground Deformations in Liquefied Layers

The deformation of ground due to the liquefaction can be evaluated in various ways such as:

- losing the shear strength
- lateral spreading of slight ground sloping
- asymmetrical settlements due to the one-dimensional reconsolidation of liquefied layers

(Lied, 2010)

Degree of Damage

Damage of the piles can be considered based on deference severity:

A) severe: dense crack through the pile, discontinuity of pile shaft, bending of bars, concrete separation. These types of failure usually cause settlement or horizontal displacement in the superstructure

B) heavy: several bending cracks at different locations in depth, dense cracking and concrete separation near the pile head. This kind of damage is caused by residual horizontal displacement of the pile head

C) light: slight bending cracks closed to piles head and other locations.

D) no damage: slight bending cracking or no cracks (Joseph, 2009).

Soil and Earthquake Properties

The pile in this research has three sections of soil. The two non-liquefiable layers at the top (surface layer) and bottom (base layer) supporting the liquefiable layer. The selected earthquakes were based on the similarity of soil in three region and in the range of high seismic hazard zone with earthquake's magnitude over 7 Richter magnitude scale (Table 1).

The OpenSeesPL software has the ability of taking several parameters to simulate the soil and earthquake properties. In this paper, the three layers of soil have been used with the height of 5 m (clay), 3m (sand) and 2 m (cohesive stiff) (Figure 1). Simulating the liquefiable soil needs the water lever from top of the loos layer (sand) (Figure 2 and Table 2).

Table 1: Earthquake properties

Name	Date	Station	PGA (g)	M
Tabas - Iran	1978	Taft	0.400	7.5
Hyogo-ken Nanbu – Japan	1995	Kobe	0. 837	7.4
Northridge -USA	1994	USGS OFR	0.843	7.2

Figure 1: Soil parameters of OpenSeesPL software

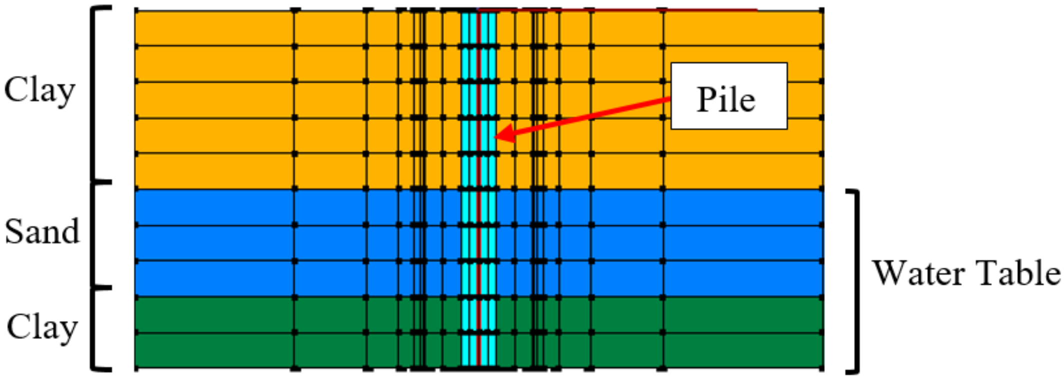

Figure 2: Three layers of soil and water table after mesh

Table 2: Soil properties

Layer of Soil	**Mass Density (Mg/m3)**	**Cohesion (kPa)** Multiply by ((Sqrt(3)/2)	**Peak Shear Strain** Multiply by ((Sqrt(2)/3)	**Number of Yield Surface**
U-Clay 2 (First layer 5 m)	1.8	75	3	20
Saturated Sand (Second Layer 3 m)	1.7	0	10	20
U-Clay 2 (Third layer 2 m)	1.8	75	10	20

Pile Detail

The total pile length was 10 m with 1 m diameter. The mass density of pile concrete has been selected 2.4 Mg/m3. The pile head connection considered to be fixed and no pile has been modeled above the ground surface. The bedrock type needs to be identified by the software that the rigid soil has been chosen. In this model only pile has been analysis without any superstructure and axial load (Figure 3).

Figure 3: Pile parameters

For analusing the pile “8-Node Brick” was the choice of soil element to mesh the different part of pile and sourrending soil. Three number of mash layers and different number of slice horizontaly and veritcaly has been selected for entire model (Figure 5).

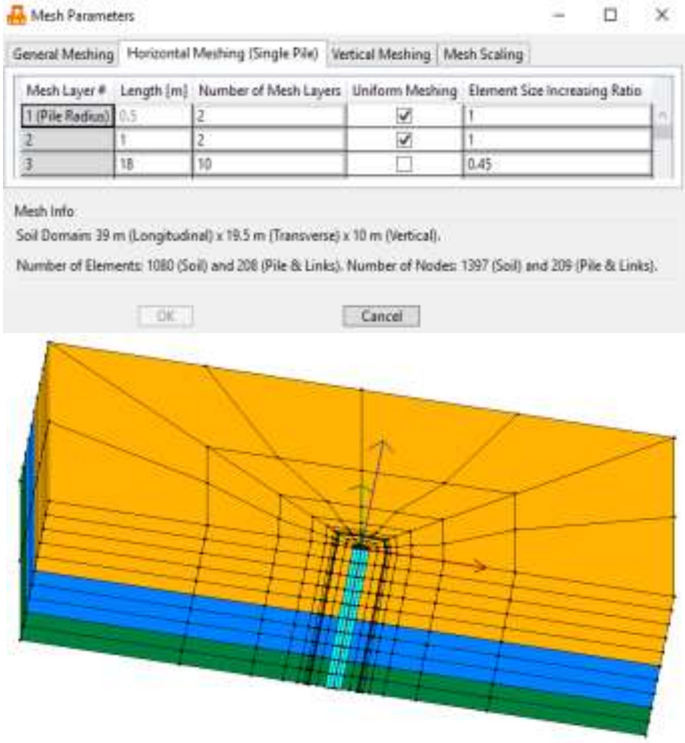

Figure 5: Mesh parameters of pile and surrounding soil

Results and Discussion

Figures 6 compare the bending moment time histories of the pile for three earthquakes. As can be seen in the below figures, the liquefaction layer with pile’s depth has a strong influence on increasing the bending moment. On the contrary, the ground deformation and inertial force had a relatively significant effect on the behavior of bending moment time history.

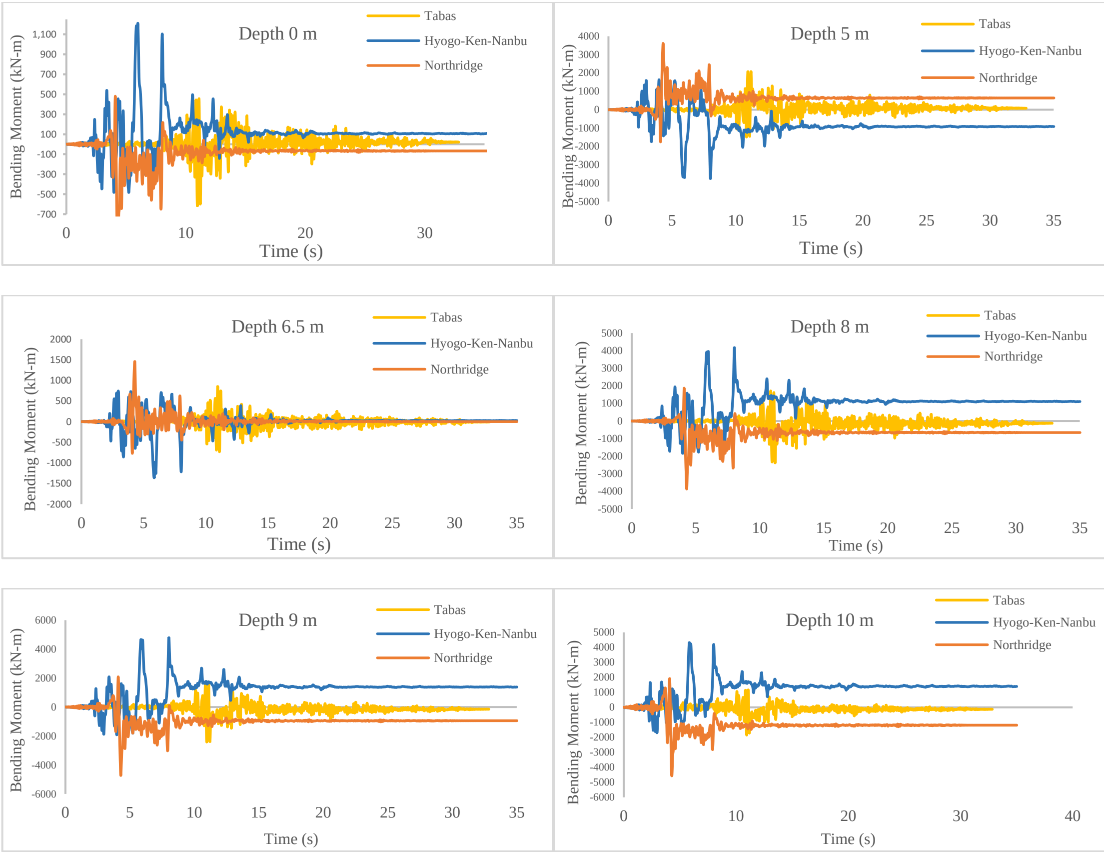

Figure 6: Bending moment time histories

The shear forces that varied through the pile show that the liquefaction has changed the behavior of the pile. Figures 7 have two main distinct behavior. Initially, by increasing the depth of pile, the shear force increased in all three earthquakes and then due to the liquefaction layer the shear stress amplitude has changed until passed this layer. It can be interpreted that the soft layer has less resistance against shear and this difference can affect the pile serviceability.

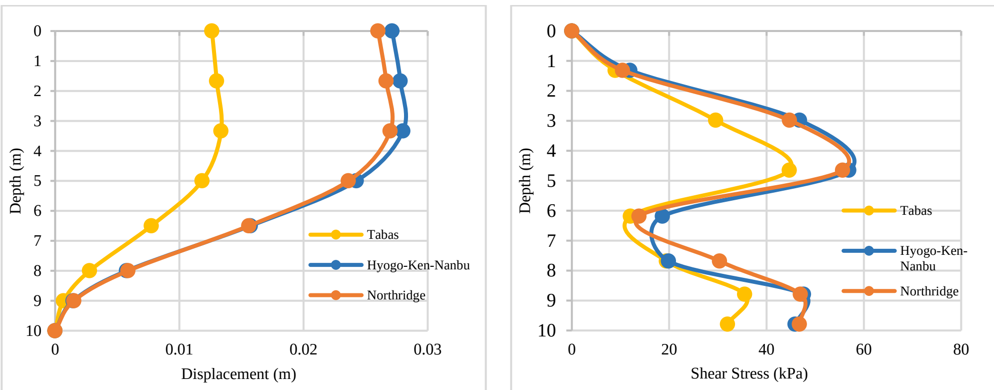

Figure 7: Shear force and displacement

Figure 8 shows the pile deformation after time history analysis. The maximum displacement happened in the soft layer with saturated sand. The most dramatic point was in the liquefiable layer, which the free field displacement appeared due to the lateral soil pressure (Karlsrud, 2012). Liquefaction during an earthquake causes a stiffness reduction in the saturated sand layer and makes a large deformation on the piles. At this time, the non-liquefiable layer moved with liquefiable soil and it applies large lateral load to the piles (Cubrinovski et al., 2006).

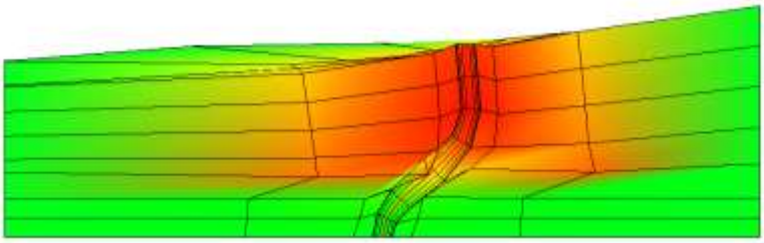

Figure 8: Pile deformation

P-Y behaviour

The p-y time histories at different depth are presented in Figures 9 for the three earthquakes. A p-y curve shows the resistance or reaction of the soil to the pile lateral displacement. The reaction force p can be obtained either from the double differentiation of bending moments or directly from the data recorded by soil pressure transducers (experimental test). In this research, the OpenSeesPL calculated force p from the double differentiation of bending moments. The y parameter that shows the pile displacements were calculated by integrating the pile rotations along with the pile.

Figures 9 display the typical interactive p-y curves for three earthquakes at different depths. Accordingly, by increasing the depth of pile the curves show a softening behavior. It is clearly observed that at 8m depth, the pile shows a large displacement in all earthquakes. This depth represents the liquefaction layer and indicates that the saturated soil has undergone a higher displacement in comparison to the other depths of the pile.

By looking at the first and last layer of soil (depth 0m, 5m and 9m), it is obvious that they had greater resistance in comparison to the liquefiable layer due to the poor cohesiveness and non-liquefaction property. Figure 9 (depth 8 m and 9 m) shows a complex behavior of different mechanism of the pile. In these Figures, hardening happened after reaching the ultimate strength. It is clear that by increasing the pore pressure, the behavior of the soil changed and after reaching the maximum pore pressure the force p decreased. The softer behavior of the pile in all earthquakes is mainly due to the high pore pressure with larger displacement.

The sand layer was loose and liquefied early in excitation in all earthquakes. In this layer, liquefaction happened early in terms of time, and the p and y time histories in below Figures show a little lateral resistance on the pile under large relative displacements. The same trend can be seen for all earthquakes that generated high pore pressures. Liquefaction did not occur completely until the acceleration reached its peak. The liquefiable layer had a relatively high strain potential upon liquefying that made the soil profile soft and in a different part of this layer, the soil acted differently. Consequently, the earthquakes in the sand layer were not completely uniform across the profile.

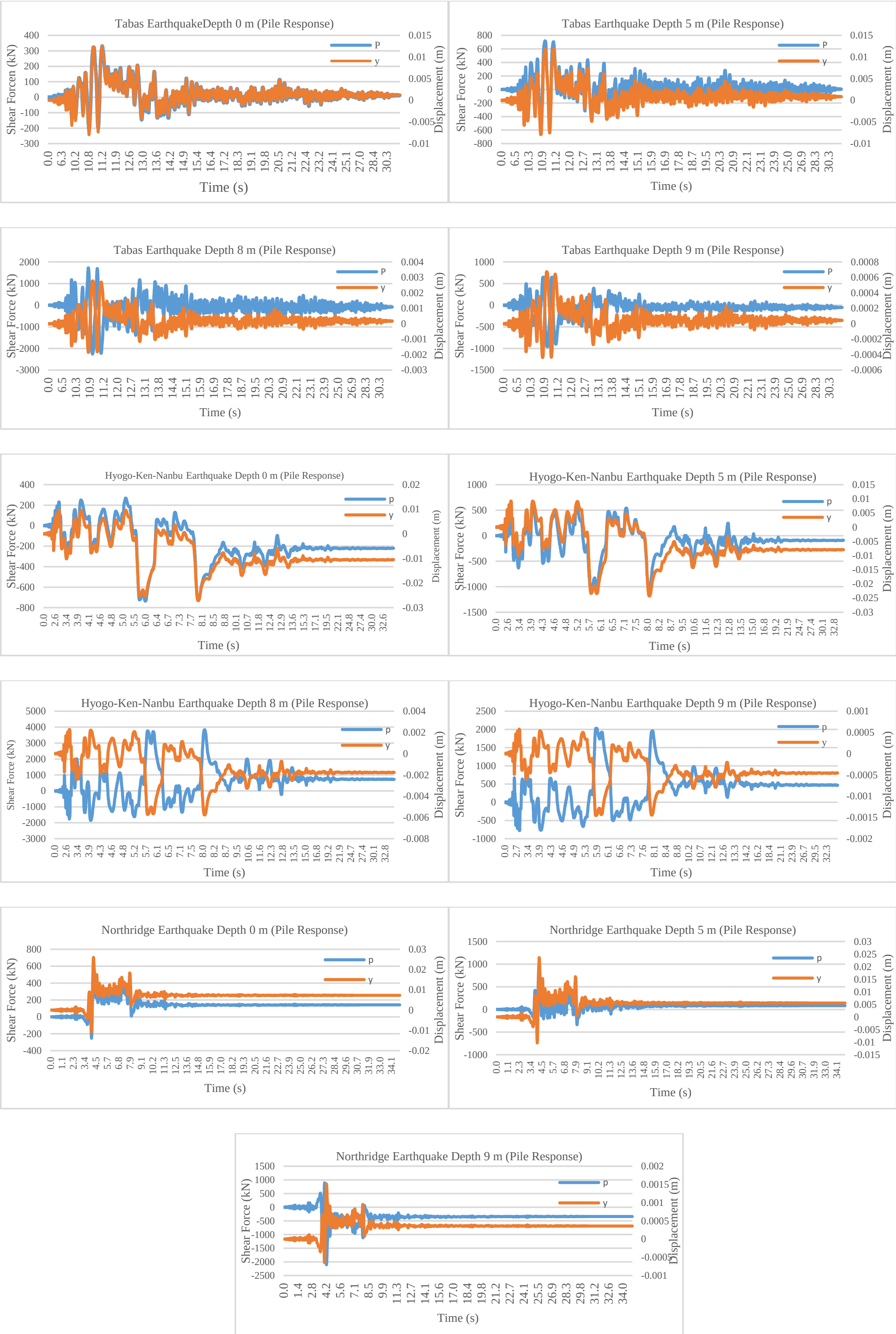

Figure 9: Shear force displacement time history

Conclusion

Piles always susceptible to damage in the layers with different stiffness. The variation of deformation in soil with different stiffness causes a large displacement in soil's layer and pile. In this regard, the properties of surrounding soil have a strong influence on the seismic interaction and pile's displacement. One of the fundamental principles of piles behavior is in the liquefaction soil, which can cause degradation in the stiffness. The pile's damage usually happens between the stiff and soft layer, where the concentrate of strain at different stiffness of the soil is high. In addition, there is a same application in the liquefiable and non-liquefiable layer. During an earthquake stress in the liquefiable layer reduces the soil stiffness.

Liquefaction is one of the most important reasons that lead to heavy damage in pile and superstructure. When the inertial load applies to the foundation, the pile is subjected to the critical situation. Experimental test and p-y analyses revealed that bending moments induced in the pile when the sand layer liquefies. Pile geometry helped reducing undesirable torsional effects during seismic excitation.

In this study, a pile has been analyses through different soil layers and earthquakes by OpenSeenPL software. The results of the pile behavior represent the interaction of soil and pile in terms of the shear force/displacement behavior, bending moment, shear force behavior of the pile in different depth and a total displacement of the pile through the depth. The soil layers comprising two clay layers with different properties and one sand layer under the water table that fully saturated. The time history analysis showed that by increasing the depth of pile the situation of soil varied and the applied stress changed through the pile length. The shear stress that related to the surrounding soil has been increased and altered dramatically, especially in saturated layers that liquefaction happened. This trend can be seen in displacement as well. However, the peak ground acceleration of earthquakes had a key role on the pile behavior. The maximum bending moment (pore pressure and displacement) in all earthquakes happened in the layer where the sand placed between two stiffer layers.

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