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Mini Review

Designing piles in soils with liquefaction capability

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ABSTRACT:

Piles in fact are like thin and resistant columns that are laterally supported by surrounding soil and there found interaction between piles and soil. Piles that passes from different layers of liquefaction soil due to the liquefaction resulted from earthquake force lose their lateral support. In these conditions the pile could be like a non-resistant column be ready for axial and shear instability. This instability and wasting the interaction between soil and pile could lead to lateral buckling of pile in weaker direction and plastic hinge. In the last years many cases of pile foundation rupture at bridges and buildings due to the liquefaction of soil layers after earthquake have been reported that caused the collapse of the structures, while these piles were designed according to valid regulations such as Japan Road Association and National Earthquake Hazards Reduction Program. Then it seems that the behavior of these piles and their analysis method is not fully known. Therefore in this research we study the buckling capacity of piles in layered liquefaction soils.

Keywords:

Liquefaction, pile, modeling, earthquake

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INTRODUCTION

Today, piles are known as one of the most commonly used and most important solutions for the foundation reinforcement and soil improvement. They are used for different types of structures such as foundation, bridge pillars, piers, etc., in the twenty first century. These compound components (stanchions) are manufactured using the most available resistant and durable materials such as steel, concrete and reinforced concrete. Piles are divided into different types in terms of shape, dimension, materials, and performance. The important part consists of reinforced concrete piles and steel piles. They perform as the end resistance of pile and frictional pile wall resistance or the combination of both which the third one has the best seismic performance and the most load capacity. Piles take place inside the soil, where they control both the structure's weight and the soil transformation of the structure location. Piles transfer the structure's weight and the soil transformation to the hard layer of the soil. Modeling, transformation, manufacturing, and performance of piles are very important, because they form the foundation of the structure, so any pile failure in any part causes damage to the entire of structure.

Liquefaction is the most important, complicated and challenging issue in seismic engineering. The performance of the pile in liquefaction soil due to pore water pressure increase and its impacts is a complicated problem. Soil resistance and hardness decrease due to liquefaction could make significant moment and shear in the pile at these soils. This phenomenon could cause considerable damage to the structures bested on pile such as bridges and buildings (Sadrkarimi, 2007). Liquefaction concept is divided into three different layers; 1. Before earthquake in the ground surface, 2. During liquefaction in sand and water spouting, 3. After liquefaction in settlement (Conlee *et al*., 2012)

In a location that consists of three layers of soil, the upper layer and lower layer are of resistant soil and the middle layer is of saturated loose sand and the pile is inside the three layers, if a quick dynamic load such as earthquake occurs in the middle layer of soil which has liquefaction potential and due to the phenomenon of lateral expansion, there is a possibility that a plastic area is made in the pile, this phenomenon is known as pile-pinning impact. In some projects the piles are designed as prone area to pinning formation all over the liquefaction layer and this design method is standard regarding United States' bridge design guide of the Multidisciplinary Center for Earth- quake Engineering Research and the Applied Technology Council (MCEER/ATC-49-1). The aim of this research is to study some basic assump-

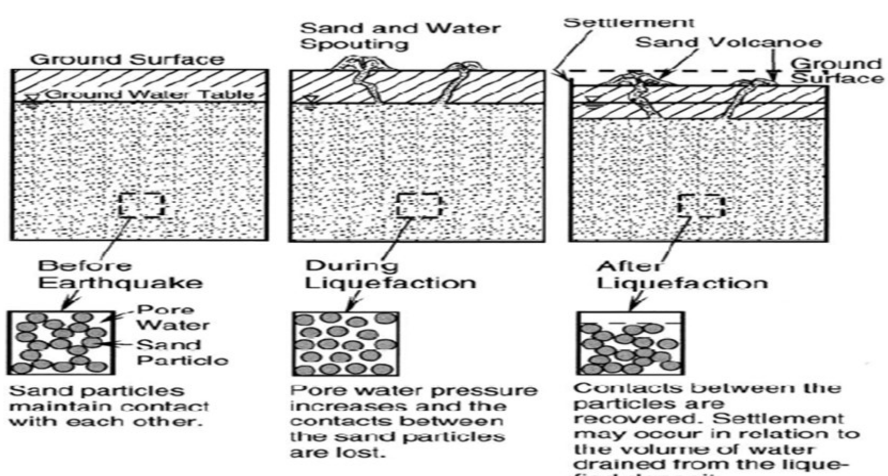


Figure 1. Liquefaction concept in three different layers; 1. Before earthquake in ground surface, 2. During liquefaction in sand and water spouting, 3. After liquefaction in settlement (Conlee *et al*., 2012)

Figure 2. The failure of Shoowa bridge in Nigata earthquake (Towhata, 1999).

tions in pile-pinning evaluation and to reach a suggestion of a simplified probabilistic framework for evaluation of displacement effects under the influence of liquefaction on bridge foundation piles. The primary sources of uncertainty are in accordance with instructions of Pacific Ocean Earthquake Engineering Research Center (PEER). The details of this problem and the approach in evaluation of bridges damages under the impact of liquefaction and pile-pinning is presented for the first time by PEER. PEER-PBEE method emphasizes on method components related to the problem (Jack Moehle and Deierlein, 2013 and Paolo *et al*., 2012).

Several primary evaluations are used before simplified framework suggestion. These primary evaluations include: seismic hazard assessment in location, liquefaction triggering assessment, and liquefaction failure potential assessment.

PEER-PBEE method is used for the impact of bridge foundation piles under the influence of displacement from lateral expansion due to liquefaction. In this research a method is presented for the lateral displacement estimation in bridge abutments due to earthquake and we can use this method to evaluate the impact of displacements on the main structure of the bridge. With this evaluation of the bridge response the damage areas of bridge system are determined and their components are assessed. This evaluation is called evaluation of bridge seismic risk under the impact of pile-pinning. In this method after modeling of the main structure, pile, soil layers, liquefaction impact and pile-soil interaction we can study liquefaction effects due to earthquake on pile buried in soil layers and evaluate the effects made in pile on seismic behavior of the main structure of the bridge. For this purpose after analyzing the above mentioned model and presenting fragility curves which is a new and powerful tool in failure probability estimation in different structural devices, we can use estimation regarding the cost of repair, breakdown and failure for different risk levels in analysis. The aim of this research is evaluation of the seismic behavior of the bridge under

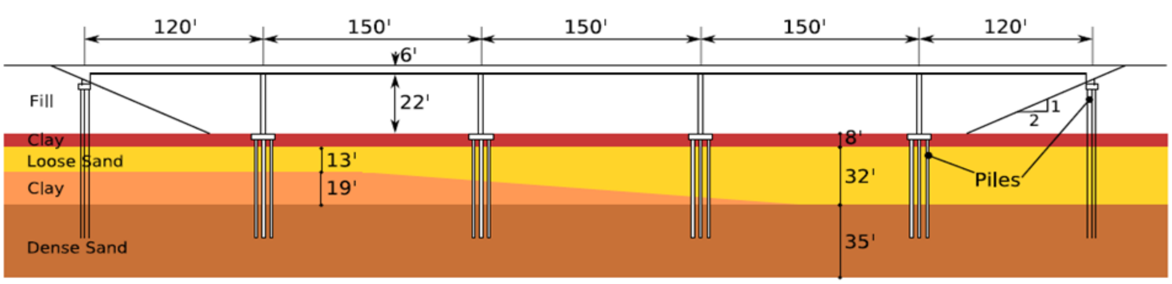


Figure 3. Bridge specifications (Karimi, 2007)

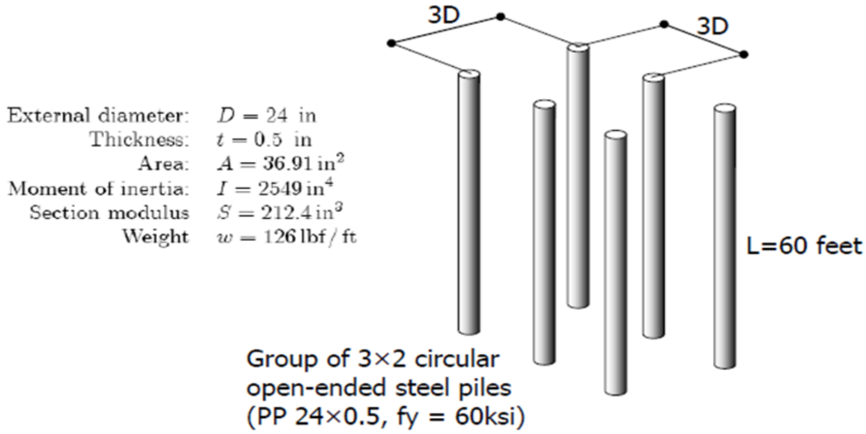


Figure 4. Pile's inside-curve dimensions and features (Mokhtar *et al*., 2014)

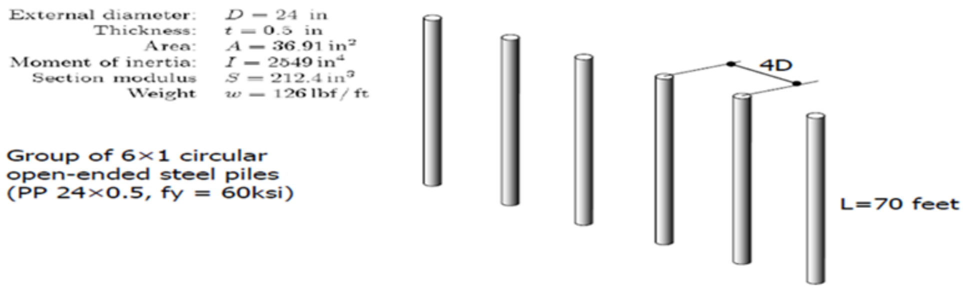
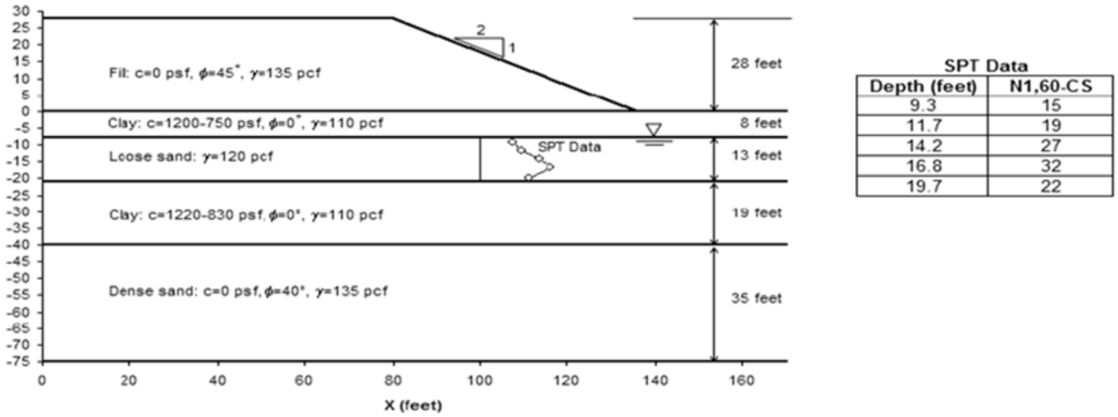


Figure 5. Piles-half-bridge characteristics and dimensions (Mokhtar *et al*., 2014)

the influence of pile-pinning due to liquefaction of soil layer around pile and understanding resistive behavior and pile displacement. Also determination of damage and failure rate due to earthquake is among the research goals (Armstrong *et al*, 2008).

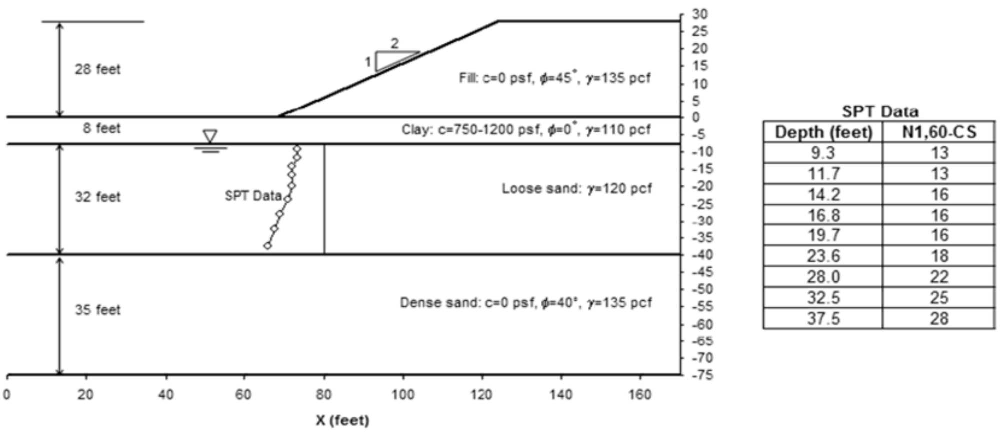
With respect to importance of this phenomenon on structures it is tried to model and evaluate it using SAP 2000 software. The studies have been done regarding this, for instance, Turner and Brandenberg (2015) studied pile – pinning and adjacent pillar interaction during lateral expansion. The studies which have been done by the authors and the others showed that Equivalence Static Analysis methods (ESA) can predict the response for lateral expansion of the bridge pillar and can identify and estimate lateral expansion. However, an important aspect of analysis which should be studied is that how deterrent force of the pillar is measured when the earth expand laterally. This research regarding the bridge problem that passes Colorado River in Mexico studied extensive field of earth lateral expansion. Finite Element Analysis (FEA) was used in order to determine influence quantity of each bridge in lateral expansion of the other bridge. The results indicate that the relatively firm pillar of the first bridge has protective effect for the second bridge and comparing the magnitude of lateral expansion, the damage decreased significantly. Also in another research, Bray and Travasarou (2007) analyzed what will be happened if soil forces are less than structure resistance. They presented a relationship to estimate longitudinal displacement in bridge abutment. And in another research which is the methodology of this research and leads to regulations publication, Japan Road Association in 1996 evaluating liquefaction material response and hypothesizing that lateral pressure distribution of 0.3 is equal to slag pressure and hypothesizing that structure resistance is smaller than soil capacity is not true.



SPT Data

Depth (feet)	N1,60-CS
9.3	15
11.7	19
14.2	27
16.8	32
19.7	22

Figure 6. The characteristics of the left half-bridge soil and dimensions (Lombardi *et al*., 2017)



SPT Data

Depth (feet)	N1,60-CS
9.3	13
11.7	13
14.2	16
16.8	16
19.7	16
23.6	18
28.0	22
32.5	25
37.5	28

Figure 7. The characteristics of the right half-bridge soil and dimensions (Keith *et al*., 2011)

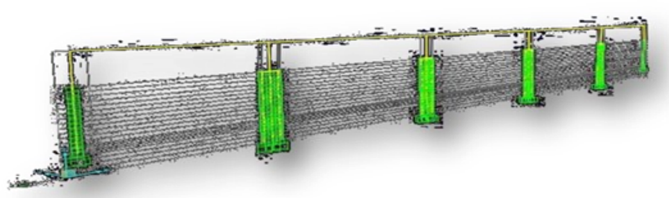


Figure 8. Model simulation in SAP2000 software (Bray and Travasarou, 2007)

Finn and Fujita (2001) in a research studied the liquefaction effect of earthquake on buried pipes and showed that the seismic behavior of buried pipes is different with ground structure. The reason is the interaction of soil and pipe. The studies that have been done on buried pipes failure proved that on contrary to other structures the load of seismic vibrations is not the main reason for buried pipes destruction, but large earth movements are the main reason of pipes failure. In other words buried pipe lines usually have the ability to tolerate earthquake waves but they can't tolerate earth large movements such as faulting, landslide, or soil liquefaction. Actually the main danger of earthquake for pipe lines include transient movement of the earth and permanent displacement of earth. In this article the impact of soil dilation angle on buried pipe is studied and analyzed, and the results indicated that pipe vertical displacement with increasing soil dilation angle in relative density of variable is dependent on the relative density of the range. Also studying the impact of soil friction

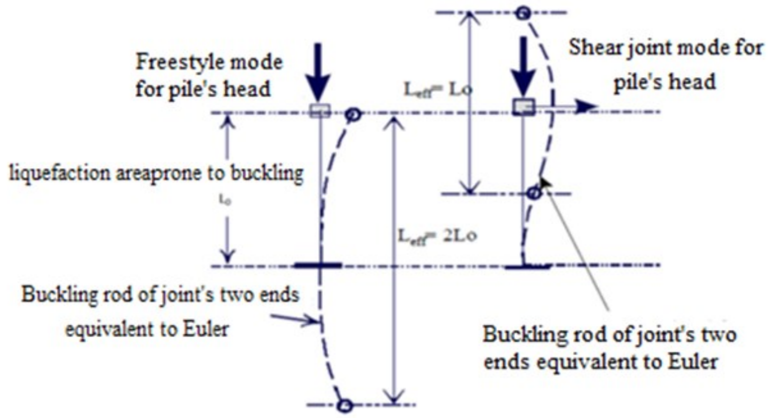


Figure 9. The schematic figure of pile buckling under the influence of liquefaction (Bhattacharya *et al*., 2005)

angle on buried pipe showed that increasing the angle of soil internal friction increase the locking force of soil particles and decrease pipe vertical displacement while liquefaction. So, using broken soil particles with sharp corners in comparison with round corner soil particles are more effective in fulfilling the objectives of this research.

METHODOLOGY

We used modeling and static pushover analysis. Soil layers and liquefaction impact have been indicated as p-y springs, the pile and the main structure of the bridge are modeled in SAP2000 software. The analysis is nonlinear (pushover). SAP2000 offers a single user interface to perform modeling, analysis, design, and reporting. Data analysis and their output are estimated and deformation and fragility graphs are obtained for different risk levels.

In this application, probabilistic methodologies usually involve three steps: 1. Establishing a model for prediction of seismic slope displacements, where seismic displacements are conditioned on a number of variables characterizing the important ground motion characteristics and slope properties; 2. Computing the joint hazard of the conditioning ground motion variables, and; 3. Integrating the above-mentioned two steps to compute the seismic displacement hazard. Focusing on the first step, the current study proposes a new relationship for seismic slope displacement, which can be cast in a probabilistic framework similar to that proposed by

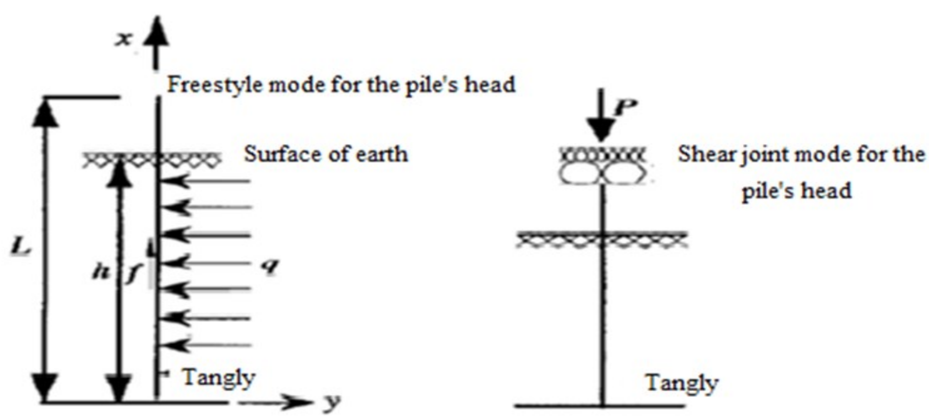


Figure 10. Pile boundary conditions (Conlee *et al*., 2012)

PEER. The proposed methodology can be used to calculate the probability of the seismic displacement exceeding a selected threshold of displacement (d) for a specified earthquake scenario and slope properties. The use of the proposed relationship in predicting seismic displacement hazard is discussed in Bray and Travasarou (2007).

It is tried that lateral load distribution on structure model is similar to what happened in earthquake and critical deformations and internal forces. In a study a research regarding Kaltrans Highway Bridge that is prone to earth lateral displacement due to soil liquefaction was tasted. The bridge that is selected for analysis consists of five span concrete structures with a deck box. It has three middle span of 150 feet and two final spans of 120 feet. The deck has six feet depth and it is on 22 feet stool.

Port Column has four feet diameter and it is reinforced with the ratio of 2% steel. Each bridge pillar is supported by a group of 3.2 open-ended steel piles with diameter of two feet, thickness of 0.5 and performance of KSI 60. Piles types were the same and some of the piles are used in half bridge but they were distributed in one row (Bhattacharya *et al*., 2005).

The soil under the left half-bridge consists of infrastructure of a hard clay soil layer and a layer of dense sand. The soil under the right half- bridge consists of thin layer of clay and a thicker layer of loose gravel. Low-density clay than the half-bridge left to the center of the bridge becomes thinner. Half bridges have 28 feet height and its domain is 2:1. Ground water is located under the clay soil layer. Loose sand layer characteristics all over the bridge with the aim of induction of liquid underground which displace earth laterally especially in right half-bridge cause extensive damage in the bridge.

Seismic hazard

Adjustment to -5% a uniform hazard spectrum for allowed failure of the soil field is used by Bhattacharya *et al*. (2005) in the analysis. This spectrum of probability risk analysis is extracted from a site in Oakland California using earth movement model by Tandel *et al.* (2012) in which possible earthquake danger analysis are shown by Seed (1976). Danger level was considered by Bhattacharya *et al*. (2008) which give the risks of 2%, 10%, and 50% in 50 years. Only the component of normal strike (parallel to bridge longitudinal direction) was considered in this two dimensional analysis. The aggregate risk in one second period showed that in all three risk levels there is earthquake danger in Heward Fault which is seven km east of site. Fault Heward has the potential of earthquake with the magnitude of 7.With respect to Bhattacharya *et al*. (2005) opinion the largest share of accidents are 6.6, 6.8 ,7.0, which respectively have the risks of 2% , 10%, 50% in 50 years. As the next section of this report shows liquefaction possibility for three risk levels was analyzed by Bhattacharya *et al*. (2005). Then a fourth risk level which is not the reason of liquefaction is added to show the impact of liquefaction in seismic performance.

The same risk spectrum is estimated for the smallest risk level by creating a linear extrapolation in Sa (soil)/ MSF in front of the space In (T_R) in which TR is a return period for each period of vibration. For PGA the regression result was linear:

$$\frac{\text{PGA (soil)}}{\text{MSF}} \approx -0.3776 + 0.1411.\ln(T_R)$$

(Bhattacharya *et al*., 2005)

After the experiment of Youd and *et al*. (2001) the maximum ground acceleration of g 0.14 is not produced in liquefaction site. Hypothesizing that Mw ≈ 6.6 then MSF ≈ (7.5/ 6.6) = 1.458.

$$\frac{0.14}{1.458} \approx -0.3776 + 0.1411.\ln(T_R) \quad \text{(Youd \textit{et al.}, 2001)}$$

$$\Longrightarrow \quad T_R \approx 29 \text{ years (Youd \textit{et al.}, 2001)}$$

A similar linear regression was done for every vibration period and Sa/MSF ratio was estimated for each period considering that TR=29 years (82% for 50 years accidents). Figure 1 to 6 shows uniform risk spectrum adjustment for soil allowed conditions and four levels danger is considered in analysis.

Designed models in softwares

For deck beam and piles used in bridge define the sections by definite menu, then with respect to information assigned on every section of bridge.

Plastic joint formation

Linear Static Analysis method (pushover) is used for analysis in the experiment cited. In this method the load on structure increases gradually according to a specific pattern. As the load increases weak points and failure modes are determined. Loading is one way but the behavior is considered as a cycle and the load reciprocating mode is improved by power-displacement function and damping estimates are considered. Observing geometry of the structure, we can study structure linear formation and plastic joint formation. In addition using push over curves we can observe base sheer-roof shift and spectral acceleration – structure spectral shift curves. SAP 2000 software has the capability to calculate the structure performance point coordinates according to special demand spectrum.

Loading conditions

In order to study the buckling behavior of piles in single layer soil, they considered horizontal reaction coefficient distribution of soil bed according to Conlee *et al*. (2012) studies:

$K_h = m_h z^{\omega} \xi^{1-\omega}$ (Conlee *et al*., 2012)

'K_h' in which the ratio of this coefficient to depth according to 'm_h' is equal to bed reaction horizontal coefficient according to kN/m^3.

In order to calculate the buckling capacity of pile we can minimize the total potential energy considering suitable evolution for piles by Reylr-Ritz method. To control different evolutions in piles, we can consider nine combinations of boundary conditions for piles head and bottom. Two of them are observed in Figure 7 to15 which is more probable than other combinations.

The stress applied from the soil to the pile was calculated according to bed reaction method as follows:

$p = m_h(h-x)^{\omega}\xi^{1-\omega}y$ (Conlee *et al*., 2012)

In this equation, 'h' is a length of pile that is in the soil, 'x' is a distance from the pile bottom and 'y' is lateral displacement.

The soil reaction which is applied to pile in unit of length is equal to calculated stress.

We consider relative hardness of 'α' which is defined as below:

$a = \sqrt{\dfrac{m_h d}{EI}}$ (Conlee *et al*., 2012)

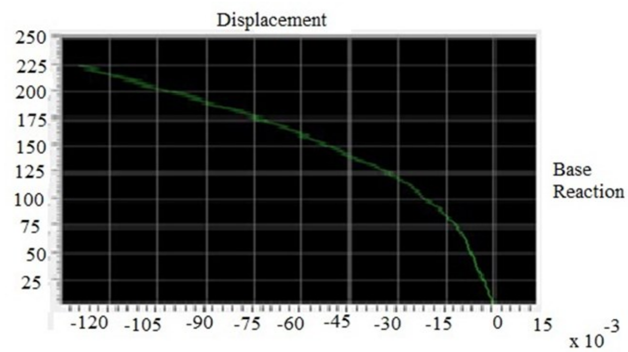


Figure 11. Curve under the load distribution pattern PUSHXHUG-1 using base shear and displacement values. Base shear curve is represented according to control point displacements (Tandel *et al*., 2012)

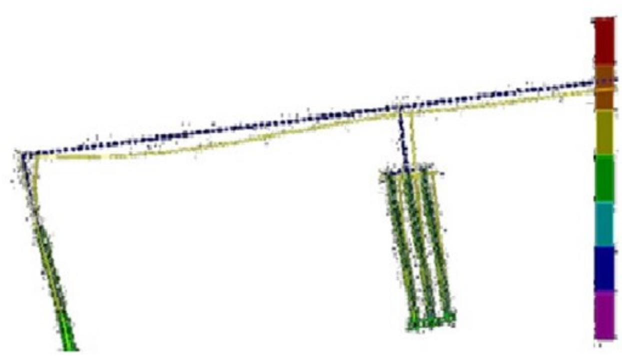


Figure 12. Modified view of the bridge (Tandel *et al*., 2012)

As it is seen in figure 12, we can observe piles, columns and bridge deck evolution

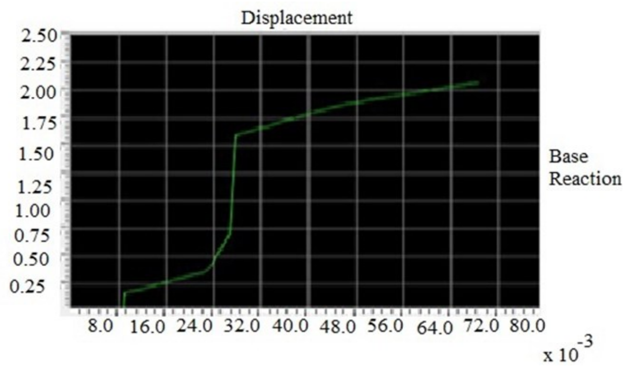


Figure 13. Structure capacity spectrum representation under load distribution pattern pushxug1 using FEMA 356 regulations (Tandel *et al*., 2012)

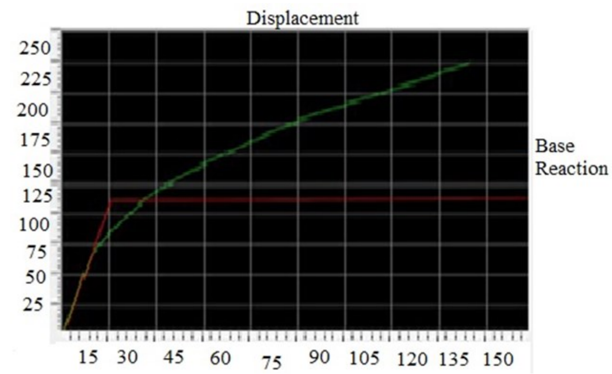


Figure 14. Capacity curve representation and structure performance point determination using displacement improvement method FEMA 356 (Tandel *et al*., 2012)

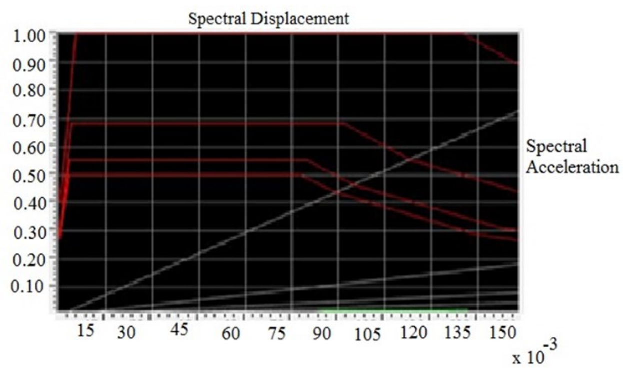


Figure 15. The representation of the capacity curve and structure performance point determination using linearization method under pushxug1with project FEMA440 (Tandel *et al*., 2012)

The collapse of piled foundations in liquefiable soil has been observed in the majority of recent strong earthquakes. Liquefiable and soft soils posed the main challenges for the design of structures. The soil–structure interaction problem can be treated as a set of decoupled plane strain problems. In practice, the analysis of laterally loaded piles are often carried out using a "Beam on Non-linear Winkler Foundation method" whereby the lateral pile-soil interaction is modelled as a set of non-linear springs (also known as p-y curves). During seismic liquefaction, the saturated sandy soil changes its state from a solid to a viscous fluid like material, which in turn alters the shape of the p-y curve. Typically, p-y curves for non-liquefied soil looks like a convex curve with an initial stiff slope that reduces with increasing pile-soil relative displacement (y) i.e., elasto-plastic softening response.

A performance-based design approach with varying levels of performance requirements were specified for the project. In this research a method is presented to calculate piles buckling force in multi-layered soil with the presence of liquefaction layer and different boundary conditions. According to the suggested method at first the liquefaction layer distance from the earth surface should be determined. If the liquefaction layer starts from earth surface, we can use the first method and calculate length factor and obtain the buckling force. If the liquefaction layer starts from a specified depth, the upper non liquefaction soil limits pile evolution and we can't use diagram to calculate the effective length factor, because in this situation with respect to hardness and thickness of upper non liquefaction layer, not only pile displacement is limited but also its rotation is limited and boundary conditions of the upper part of pile is variable between free mode and clamped mode.
Pore water pressure causes soil liquefaction under the end of the pile. As a result, the pile is sunk into the soil and the resistance under the end of the pile acts contrary to the engineering demand and reduces the capacity of the pile. In other words, the capacity of the pile is due to the resistance of the pile wall, which is also due to the effective pressure on the soil layers.

In order to calculate pile buckling force the buckling differential equation resulted from minimizing the latent energy in layered soil should be solved. As mentioned a program is prepared for this reason that we can calculate pile buckling force in linear range accurately.

CONCLUSION

The formation of pore water causes liquefaction which could be due to static loading or periodic loading. With respect to soil density and subsidence due to earthquake and liquefaction, soil and pile subsidence is more than static mode (up to 10 times). The hypothesis that structure resistance is smaller than soil capacity is not true.

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