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Analyzing the dynamic behavior of bored pile foundations in liquefiable soils using the finite difference method

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Abstract- In sandy saturated soils which are at the risk of earthquake, one of the most dangerous phenolmenon for structures is liquefaction . In order to prevent this phenolmenon and protect structures , pile foundation can be used. So we have to analyze the liquefaction effects on dynamic behavior of these foundation. In the present study , we use two- dimensional finite difference software for numerical analysis of concrete pile , with regard to nonlinear model of liquefible soil. In the following research the parametric study is focused on the effective parameters on the behavior of pile such as pile diameter and thickness of liquefible layer. Finally the scale and quality of each parameters influence on the seismic response of pile has been studied. Results are presented with increasing the thickness of liquefible layer exceeds value of lateral displacement of pile head and this increase will be more piles with less diameters. Also if the thickness of the liquefying soil layer is much, increasing the diameter helps us to reduce lateral displacement. It is found for free- head piles, irrespective of the thickness of the liquefying soil layer, the maximum bending moment is developed at the interface between the liquefying soil layer and non liquefying soil layer.

Keywords- pile, liquefaction, earthquake, numerical analysis

Introduction

As one of the most important geotechnical issues, one can refer to piles as numerous studies have addressed and are addressing new computation and implementation methods related to piles. In recent decades, the use of deep foundations or pile foundations has increased significantly in countries [1].

In addition to conventional structures such as bridges for which deep foundations have been used in the distant past, the expansion of ports in the southern and northern parts of Iran, the implementation of offshore structures in the Persian Gulf region, as well as large investments in the Oil and petrochemical resources in the southern coast of Iran have increased the need to use piles dramatically. According to Iran's Standard No. 2800 (Iranian Code of Practice for Seismic-Resistant Design of Buildings), these areas are regarded as those where the risk of seismicity is high or very high, and they are mostly covered by loose sand with no cohesion and little silt that is placed below the groundwater table. On the other hand, in sandy soils, severe seismic stresses caused increased pore water pressure, resulting in decreased soil strength, reduced soil stiffness, and the occurrence of liquefaction.

Depending on the level of liquefaction severity, the pile foundation may experience significant movements considering the liquefiable soil layer in the design, the effects of which on deep foundations are very destructive and costly. Recently, a series of laboratory (centrifuge test and shaking table test) and numerical research has been carried out to investigate the performance of piles or groups of piles in liquefiable soils and the effects of liquefaction on such structures [2].

Numerous methods have been proposed so far to improve the liquefaction resistance of sandy soils. The use of pile foundations is considered one of the efficient techniques used to increase the static load-carrying capacity of weak soils by transmitting the load from the structure to stronger underlying layers. Since piles have much higher shear strength than soils, they can improve the liquefaction resistance of sandy soils [3]. Therefore, it is required to investigate the extent to which the use of deep foundations can be useful in reducing the liquefaction potential of sandy soils [4].

Most of the previous studies have addressed single piles or small pile groups. On the other hand, researchers have provided no methods to consider the effects of piles or pile groups on the liquefaction of sandy soils [5]. Therefore, one can clearly understand the necessity of conducting numerical simulation studies and evaluating the effects of this structural element on soil liquefaction, especially under seismic loading.

The present study aims to analyze the dynamic behavior of bored pile foundations in liquefiable soils using the finite difference method. The basic analytical model is composed of a layer of saturated sandy soil reinforced with a pile. The model is subjected to superimposed load. To match the model to the real world, the analyses are performed step by step. Then, the effects of the pile diameter and the liquefiable layer thickness on the soil liquefaction are examined by applying the acceleration map of a real earthquake to the models and performing a parametric analysis.

Method

Modeling soil-pile structure

After examining the performance of the FLAC 2D software in accuracy, this section numerically models soil-pile structure and liquefaction for dynamic analysis. The present study aims to analyze the dynamic behavior of bored piles in liquefiable soils using the finite difference method. For this purpose, the following conditions must be considered. In general, these analyzes are performed in 4 stages:

I. Determining the initial equilibrium state in the soil

II. Determining the equilibrium state after the installation of the pile

III. Applying an earthquake and examining the soil-pile structure response during shaking assuming the conditions where the liquefaction of the materials is not likely.

IV. Applying an earthquake and examining the soil-pile structure response during shaking assuming the conditions where liquefaction occurs.

3-4-1- Modeling soil-pile structure in FLAC 2D program

The model was developed in FLAC 2D V.5 program prepared by Itasca company assuming a flexible bed. In this research, according to Figure (1), a soil profile with a length of 60 m and a depth of 20 m was considered in 2 layers (a loose layer at the top and a dense layer below it), and a vertical concrete pile of a 16-m length in placed inside it in such a way that 15 meters of the pile is placed inside the soil and 1 meter is above the ground surface. The properties of all the materials are presented later. A vertical load of 200 kN is placed on the pile head and the underground water level is assumed to be the same as the ground level.

Considering different states such as the pile diameter and the thickness of the liquefiable layer, the upper part of which is liquefiable, 12 models were developed, as presented in Table (1).

Table 1- Different soil-pile structure models

Pile diameter	0.6m				0.8 m				1m			
Liquefiable layer thickness	10m	8m	6m	4m	10m	8m	6m	4m	10m	8m	6m	4m

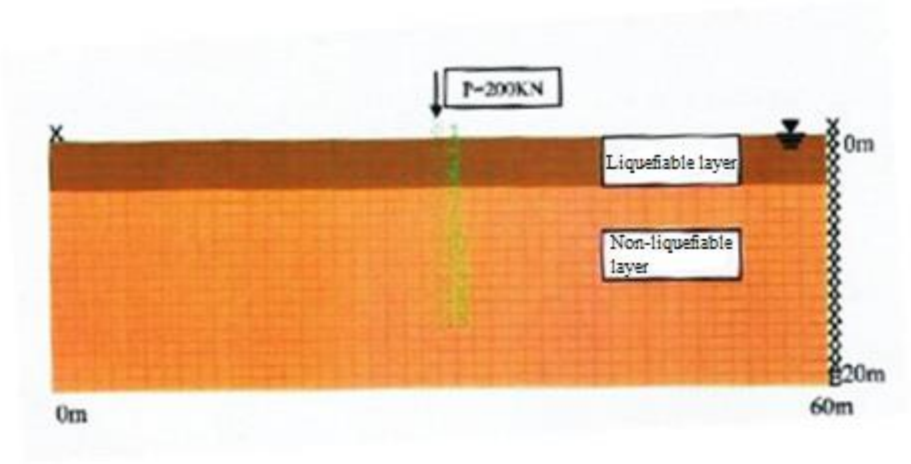


Figure1-The model geometry

The sizes of the elements in the soil-pile structure model

The elements used in soil modeling are quadrangular. To avoid numerical errors in computations, most of the elements were tried to be square. In rectangular elements, the aspect ratio (the longer side/shorter side ratio) is less than 5, although this ratio can be up to 10.

To determine the size of the elements in the model using the theory of shear wave propagation in the environment and the frequency that should be accurately modeled in the dynamic analysis, the size of the elements can be estimated using the following equation:

$$f=\frac{c\,s}{10\times\Delta l} \qquad (1)$$

Where, C s is the velocity of the shear wave in the environment, f denotes the frequency that should be modeled accurately, and ΔL is the dimensions of the finite difference element.

$$C\,s=\frac{\sqrt{G}}{P} \qquad (2)$$

$$G=\frac{RE}{2(1+V)} \qquad (3)$$

In Eq. (2), G denotes the shear modulus of the object, and P is the bulk density of the object, and in Eq. (3), E is the modulus of elasticity and V denotes Poisson's ratio of the material.

To determine the dimensions of the finite difference elements, in addition to the above equations, other models with the same dimensions and properties and different element sizes were developed. Although the models with smaller elements can accurately model a greater frequency range, they need a lot of time to perform dynamic analysis. Therefore, among the models developed, that model performing the analysis in a shorter time while maintaining the accuracy of the problem is selected.

Since earthquake frequencies are within the range from 0.4 Hz to 25 Hz, considering the dimensions of the selected elements, the accuracy of the intended frequency should not exceed the aforementioned range.

On the other hand, since soil includes different materials, as presented in the tables in the next section, there are different shear moduli and bulk densities. For this purpose, the materials with the lowest C s are used as a representative. Then, C s is calculated for different materials.

Loose sand: P= 1470 kg / m3 10 6 Pa× G= 9

Dense sand: P= 1800 kg / m3 10 6 Pa× G=9

$$\rightarrow Cs=\frac{\sqrt{9\times10\ 7}}{1470}=247.53\ m/s=$$

$$\rightarrow Cs=\frac{\sqrt{30\times10\ 7}}{1800}=408.24\ m/s$$

According to the obtained values, the minimum C s, which belongs to loose sand, is selected as a representative. Considering that the maximum frequency of the earthquake is about 25 Hz, according to Eq. (3), we have:

$$F=25=\frac{248}{10\times\Delta l}=\Delta l\sim1m$$

This means that the minimum length of soil elements should be greater than 1 meter. Otherwise, a filter is needed.

The number of zones in the soil-pile model

Since the modeling was carried out in the FLAC 2D software, and the operating memory used by this software is 24 megabytes, the maximum number of runs that can be meshed is around 14,000 zones. According to the abovementioned, the zones generated in the intended models are within the range of 1500 to 2000 zones.

Tables 2 and 3 present the properties of piles and soil

Table 2- The mechanical properties of the soil for numerical analysis

Properties	Loose sand	Dense sand
Dr (%)	45	75
Dry density (kg/ m3)	1470	1800
Porosity	0.43	0.37
Shear modulus, G (MPa)	9	30
Bulk modulus k (MPa)	15	50
Friction angle (ϕ)	26	38
Permeability (m/s)	10 -9× 8	10 -9× 5
(N1) 60	9	25

Table 3-The properties of piles for parametric analysis

Properties	Dp= 0.6 m	Dp= 0.8 m	Dp = 1 m
Pile length below ground (m)	15	15	15
Pile length above ground (m)	1	1	1
Density (kg/ m3)	2500	2500	2500
Flexural strength, fy (kpa)	$10^{4}\times 1$	$10^{4}\times 1.12$	$10^{4}\times 1.12$
Yield moment of pile, my(kn.m)	237	560	1099
Modulus of elasticity, ep (kpa)	$10^{4}\times 3$	$10^{4}\times 3$	$10^{4}\times 3$

Properties	Dp= 0.6 m	Dp= 0.8 m	Dp = 1 m
Moment of inertia, ip (m4)	0.006	0.02	0.049
Pile perimeter (m)	1.885	2.513	3.142
Cross–section area, ap(m2)	0.283	0.502	0.785

Assigning the Finn model to soil

Since the present research aims to investigate pile behavior in liquefiable soils, liquefaction was assigned to the intended soil layers considering different models. For this purpose, the Finn model was used in the FLAC 2D software, and the relevant equations were presented in the previous sections. Figure (2) shows a sample of a model developed with a 6-meter thick liquefiable layer.

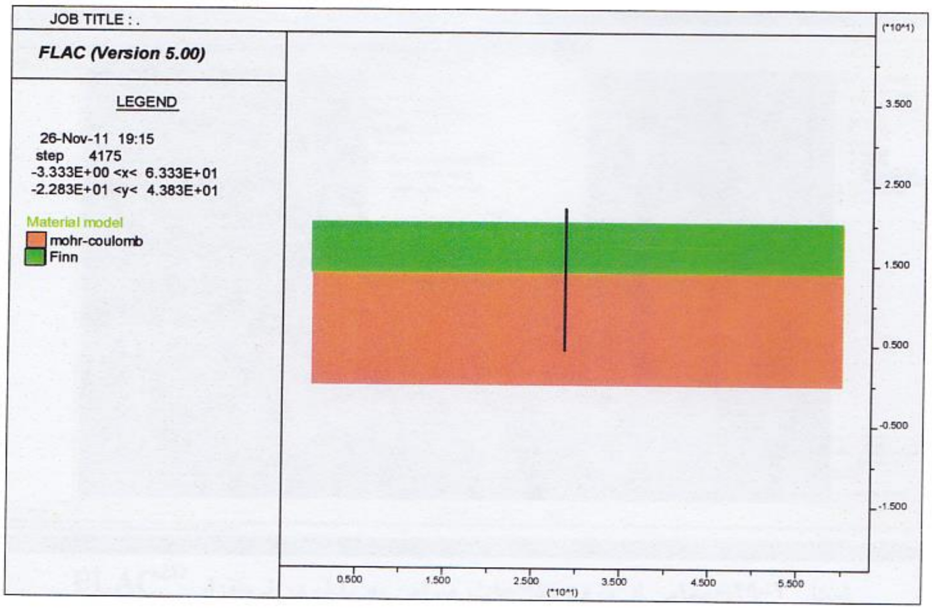


Figure 2 – A sample of a model developed with a 6-meter thick liquefiable layer

Since significant deformations occur in liquefiable soils, in this step, the analysis is performed with a large strain mode using the Settings/mech tool. Moreover, since the analysis is based on the assumption of undrained conditions, the bulk modulus of water increases until it becomes an incompressible fluid. So, the bulk modulus of water is increased to 0.2 GPa using the GW Settings tool.

Dynamic analysis of the soil-pile model

In the present study, the acceleration map of the Bam earthquake with a maximum acceleration of 0.5 g was used for dynamic analysis. This acceleration map includes 6007 points with time steps of 0.005 seconds. Totally, nearly 30 seconds were recorded on this map. To prevent some problems due to the assumption of a flexible bed, the time history of stress was used as a dynamic stimulus for the lower boundary of the soil-pile model.

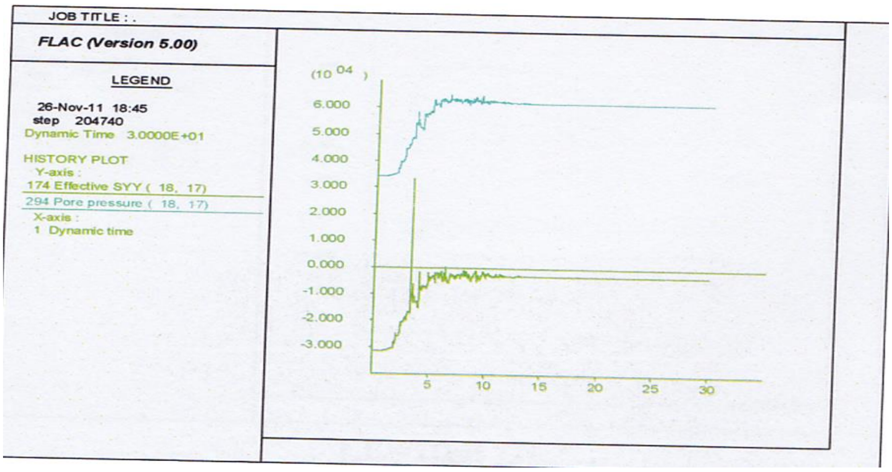
To prevent the wave reflection error from the side boundaries, free-field boundaries were used using the Apply/free-field tool in the in situ menu. These boundaries allow for reducing the dimensions of the soil from the sides.

To absorb downward earthquake waves, the lower boundary of the model was made flexible in the x and y directions using the in situ / Apply menu.

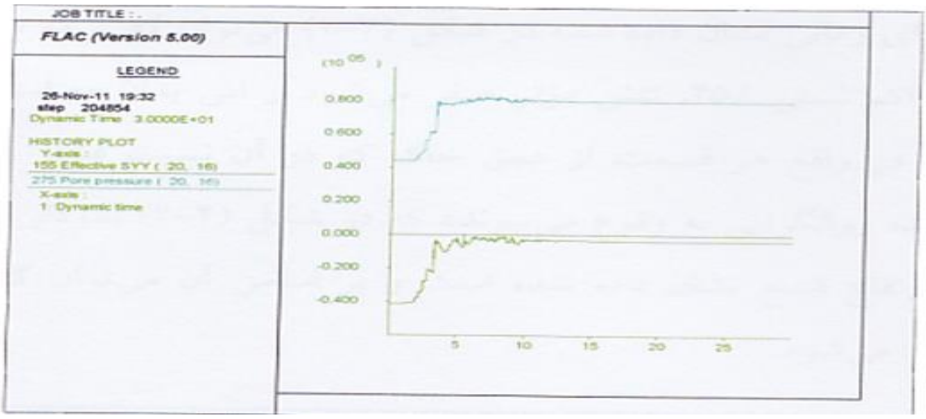
With all these steps, the soil-pile model was prepared for dynamic analysis, which was carried out using the Run/solve tool. After completing the dynamic analysis, a set of graphs, histories, and tables were obtained as results, which are analyzed and discussed in the next section.

Results

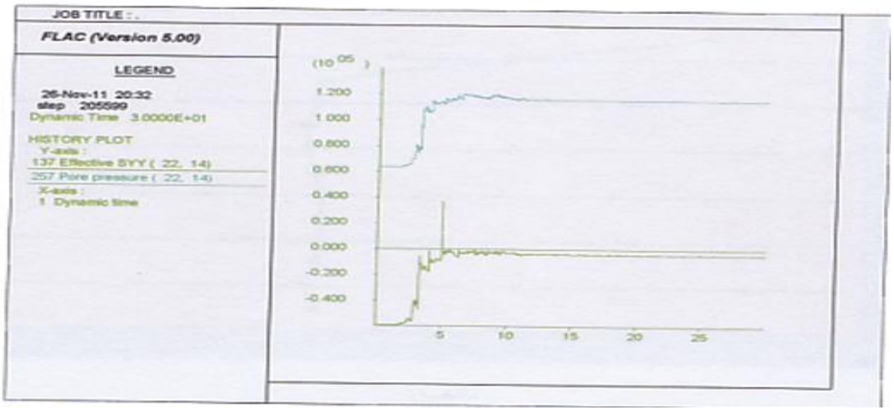
Investigating the occurrence of liquefaction due to the earthquake



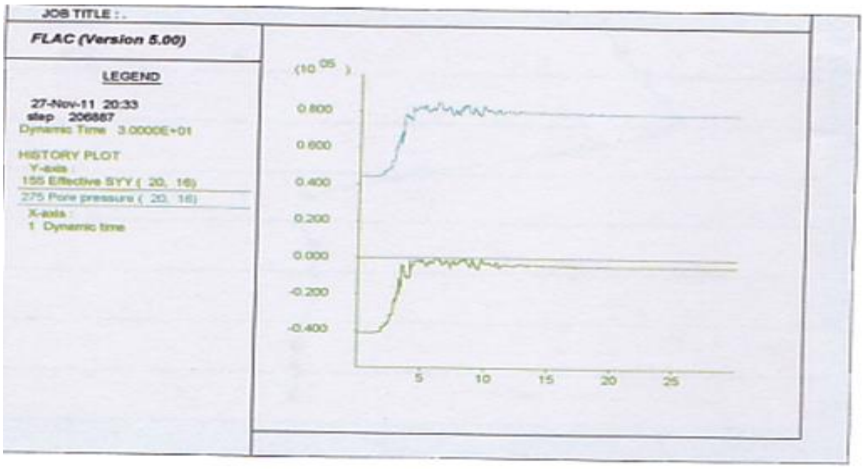
A- LL= 4M



B- LL= 6M



C- LL=8M



D- LL= 10M

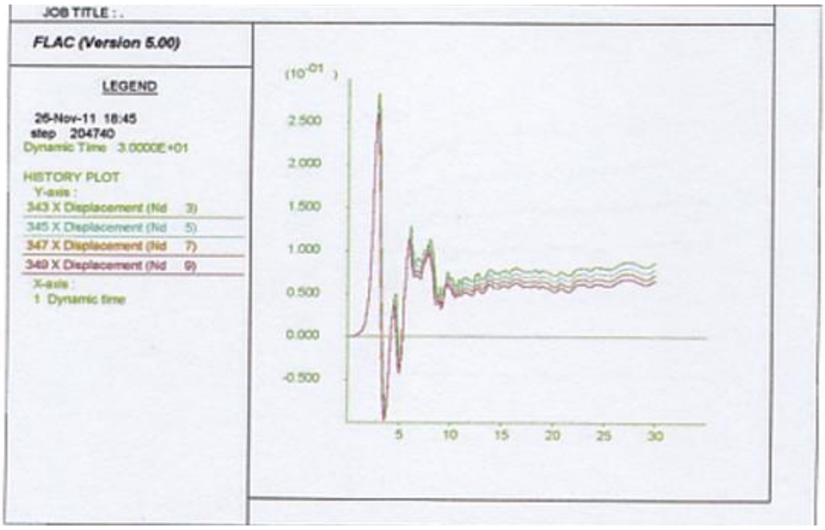
Figure 3- Pore water pressure and effective stress relative to time

According to the time histories shown in Figure (3), it can be said that in all thicknesses, the effective stress becomes zero in the center of the liquefiable layer with a relative density of 45%, meaning that sand boils and liquefaction occur.

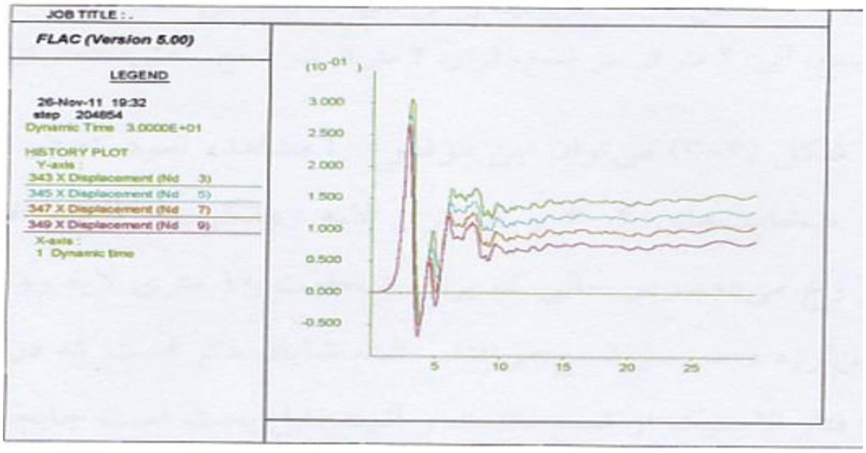
Investigating the horizontal displacements of piles in soil due to the earthquake

The graphs examined in this section include the horizontal displacements of piles due to the Bam earthquake [6].

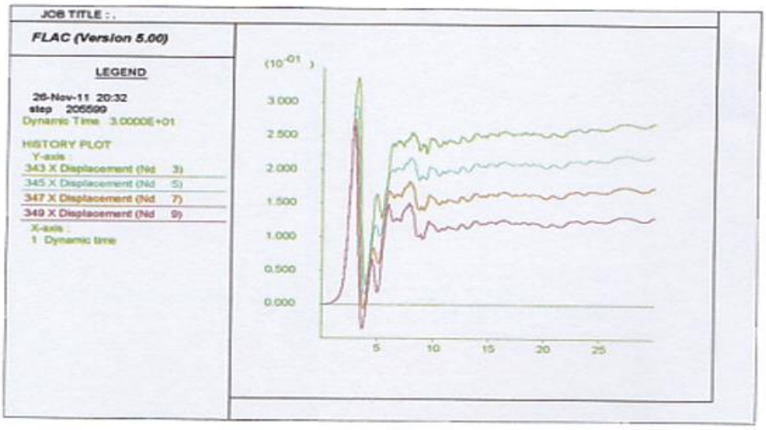
In the graphs presented in Figure (4), the time history of the lateral displacement of the pile at various heights was investigated relative to the changes in the liquefiable layer thickness, considering a fixed pile diameter and the results obtained are described in the following.



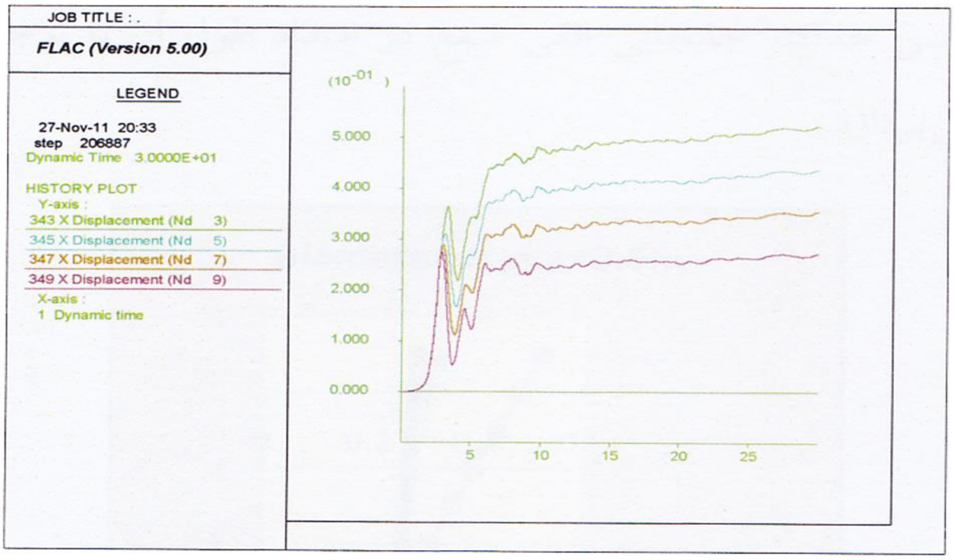
A- D = 0.6M - LL = 4 M



B- D = 0.6 - LL = 6 M



C- D = 0.6 - LL = 8M



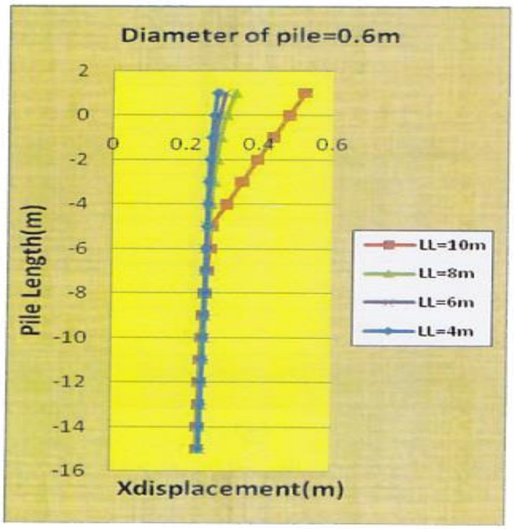
D- D = 0.6 M - LL = 10 M

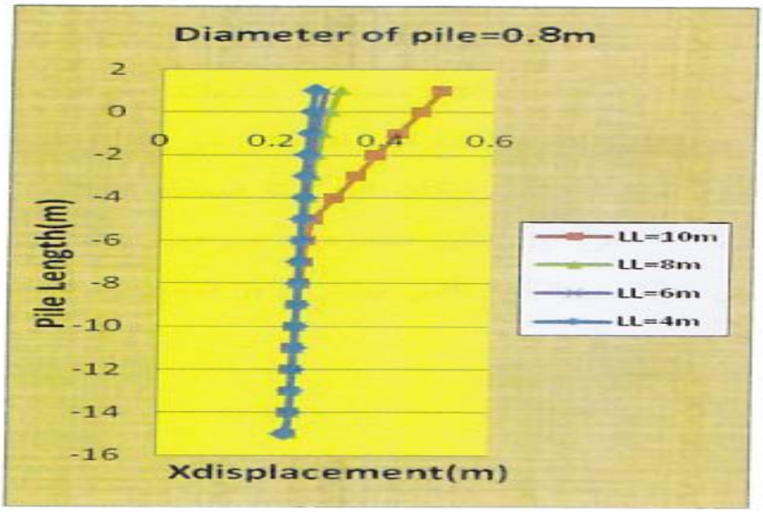
Figure 4- The time history of the lateral displacement of the pile

(Green: pile head, Blue: 2 m from the pile head, Red: 4 m from the pile head, Purple: 6 m from the pile head)

According to graphs presented in Figure (4), one can find that for the liquefiable layer thicknesses of 4, 6, and 8 m, the maximum horizontal displacement of the pile occurred in the elastic zone, i.e. the third second of the earthquake, and at the pile head. While for the thickness of 10m, it occurred in the plastic zone, at the end of the earthquake, and the pile head. It should be noted that in the liquefiable layer thicknesses of 10 m, the elastic behavior of the pile cannot be expected and what can be discussed is the residual displacement.

The graphs in Figure (5) show the maximum horizontal displacement of the pile along its length relative to the changes in the pile diameter and the liquefiable layer thickness.





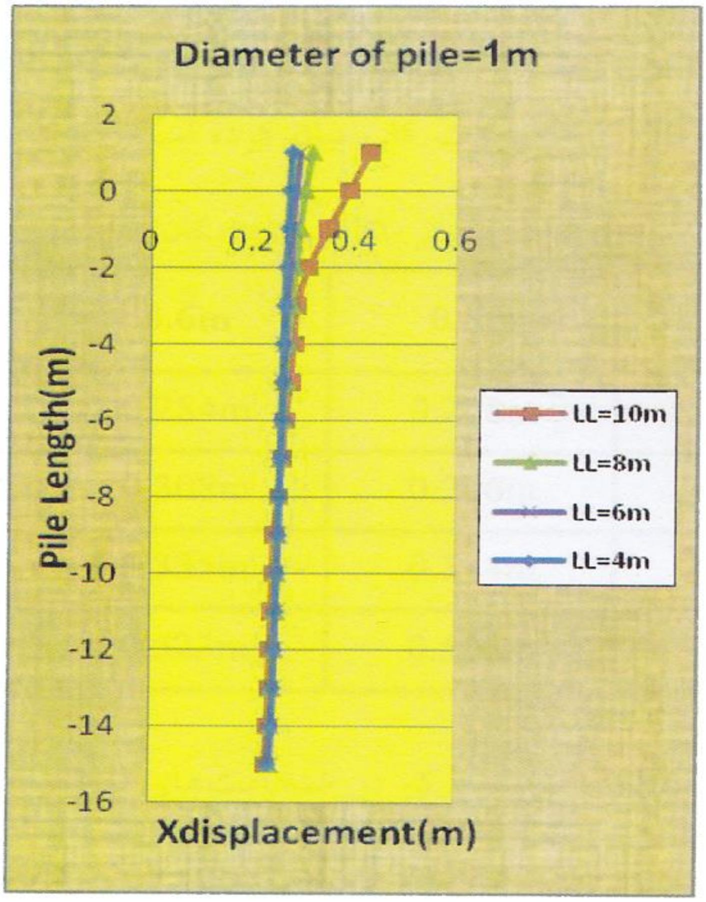


Figure 5. The maximum horizontal displacement of the pile along its length

Comparing the curves in Figure (5A) shows that for the liquefiable layer thickness of 6, 8, and 10 m, the horizontal displacements of the pile head increased by 7%, 17%, and 84%, respectively, compared to the thickness of 4 m. Similarly, the curves in Figure (5B) show 6%, 16%, and 82% increases, respectively. And, in the curves in Figure (5C), one can see 5%, 14%, and 55% increases, respectively. These percentages indicate that the increase in the liquefiable layer thickness results in the increased horizontal displacement of the pile, and this increase is greater for piles with a smaller diameter. Also, up to the liquefiable layer thickness of 8 m, one can see that the increase in the horizontal displacement of the pile follows a slow trend while increasing the thickness from 8 to 10 m is accompanied by a sharper upward trend because the reduction in the depth of fixity of the pile results in the increased lateral pressure of the liquefiable soil on the pile.

Table (4) shows the maximum horizontal displacement of the pile head both in the elastic and plastic areas in different states. The results are analyzed and discussed in the following.

Table 4-Maximum horizontal displacement of the pile

LL D	0.6M	0.8M	1M
4M	0.284 M	0.278 M	0.277M
6M	0.308M	0.296 M	0.293M
8M	0.355M	0.324 M	0.316M
10M	0.523M	0.508 M	0.430

According to Table (4), in the liquefiable layer thicknesses of 4, 6, and 8 m, increasing the pile diameter is not significantly effective in reducing its displacement while in the liquefiable layer thicknesses of 10 m, increasing the pile diameter from 0.6 meters to 1 meters results in an 18% decrease in the horizontal displacement of the pile head, indicating that if the depth of the liquefiable layer is large, increasing the pile diameter will be useful.

Investigating the bending moment created on the pile due to the earthquake

Figure (6) shows the bending moment created in the pile section throughout its length from the beginning second to the end of the earthquake for one of the models.

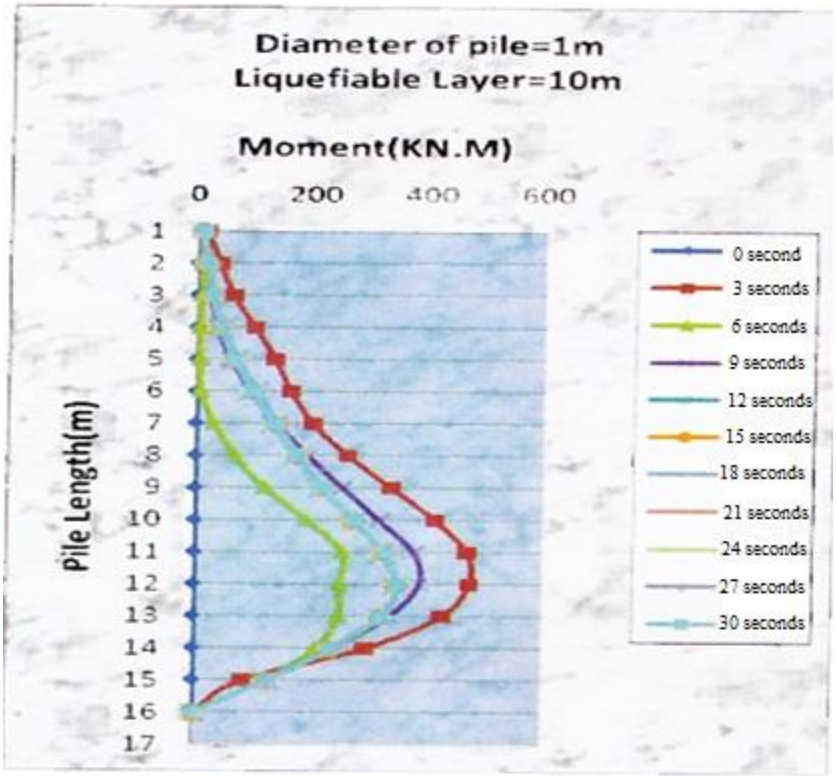
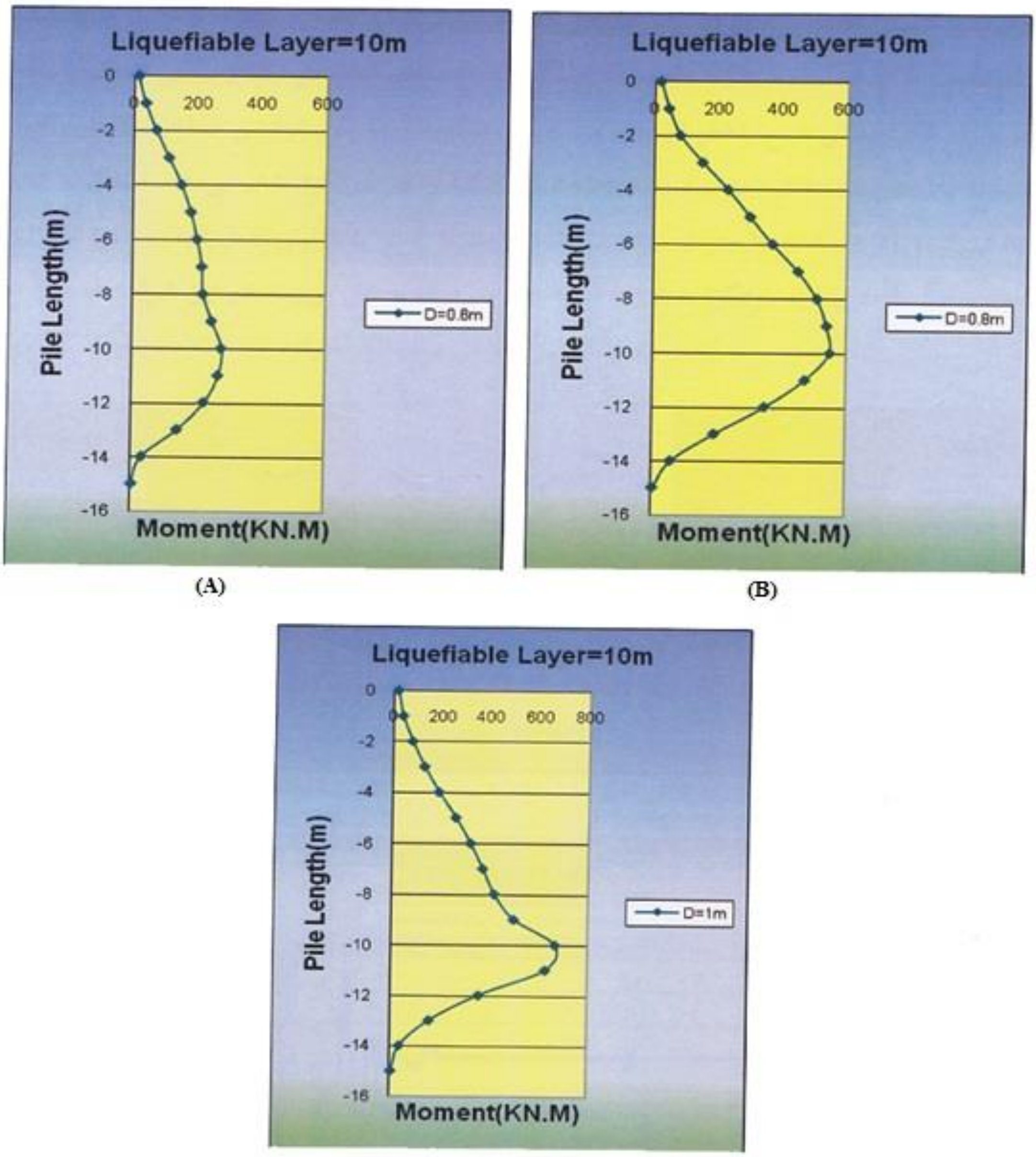


Figure 6. Changes in bending moment along the pile length during the earthquake

As seen in Figure (6), the maximum bending moment on the pile occurs nearly at the boundary between the liquefiable and non-liquefiable layers at the third second of the earthquake.

The graphs in Figure (7) show how changes in the pile diameter affect the maximum bending moment along the pile length, considering a fixed liquefiable layer thickness.



(A) (B)

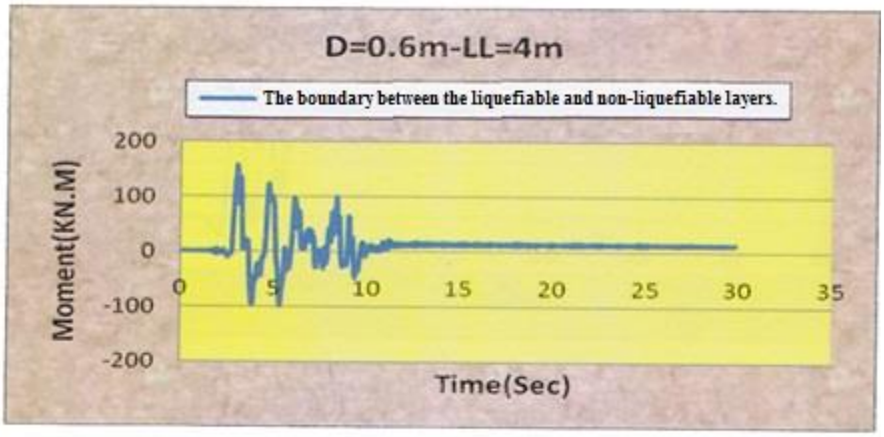
(C)

Figure 7- Variations in the maximum bending moment along the pile length

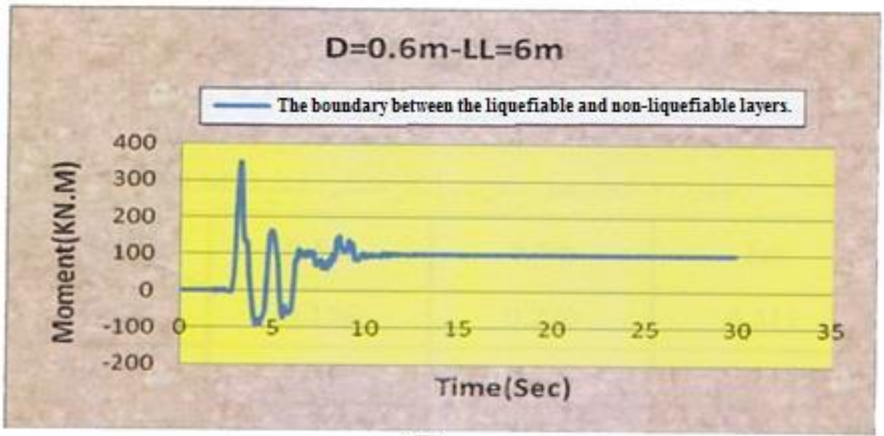
The curves in Figure (7) show that an increase in the pile diameter from 0.6 m to 0.8 and 1 m, results in a 96% and 139% increase in the maximum bending moment, respectively.

Therefore, it can be concluded that as the pile diameter increases, the bending moment created on the pile increases because its stiffness increases, and the stiffness is directly related to the moment.

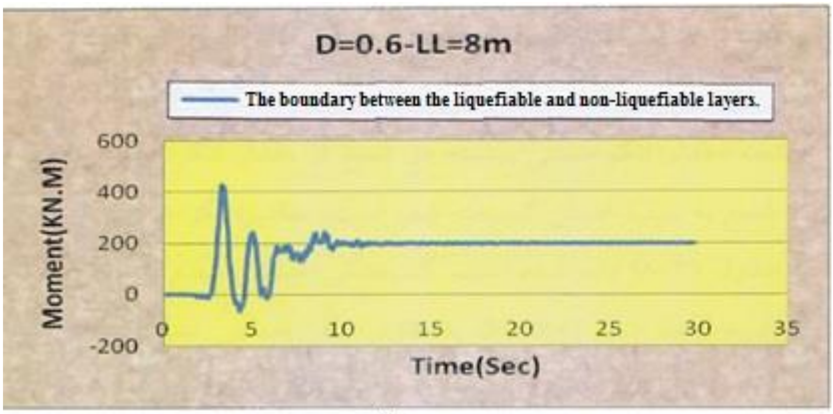
Figure (8) shows the increasing effect of the liquefiable layer thickness on the bending moment of the pile with a constant diameter at the boundary between the liquefiable and non-liquefiable layers. As seen in the time history of the moment graphs, the moment increases with increasing the liquefiable layer thickness from 4 m to 8 m while it reduces with an increase in the layer thickness from 8 to 10 m, indicating that the liquefiable layer thickness of 8 m will be the critical thickness for the moment.


D=0.6m-LL=4m
The boundary between the liquefiable and non-liquefiable layers.
Moment(KN.M)
200
100
0
-100
-200
0
5
10
15
20
25
30
35
Time(Sec)

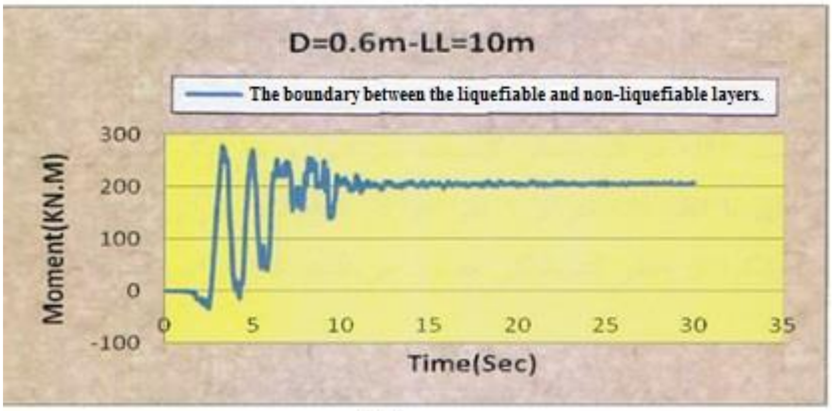
(A)


D=0.6m-LL=6m
The boundary between the liquefiable and non-liquefiable layers.
Moment(KN.M)
400
300
200
100
0
-100
-200
0
5
10
15
20
25
30
35
Time(Sec)

(B)


D=0.6-LL=8m
The boundary between the liquefiable and non-liquefiable layers.
Moment(KN.M)
600
400
200
0
-200
0
5
10
15
20
25
30
35
Time(Sec)

(C)


D=0.6m-LL=10m
The boundary between the liquefiable and non-liquefiable layers.
Moment(KN.M)
300
200
100
0
-100
0
5
10
15
20
25
30
35
Time(Sec)

(D)

Figure 8. The time history of the maximum bending moment created on the pile with variable liquefiable layer thickness

Table (5) shows the maximum bending moment of the pile for different soil-pile states. According to this table, for all pile diameters, increasing the liquefiable layer thickness up to 8 m results in an increased maximum bending moment while it decreases with an increase in the liquefiable layer thickness from 8 m to 10 m.

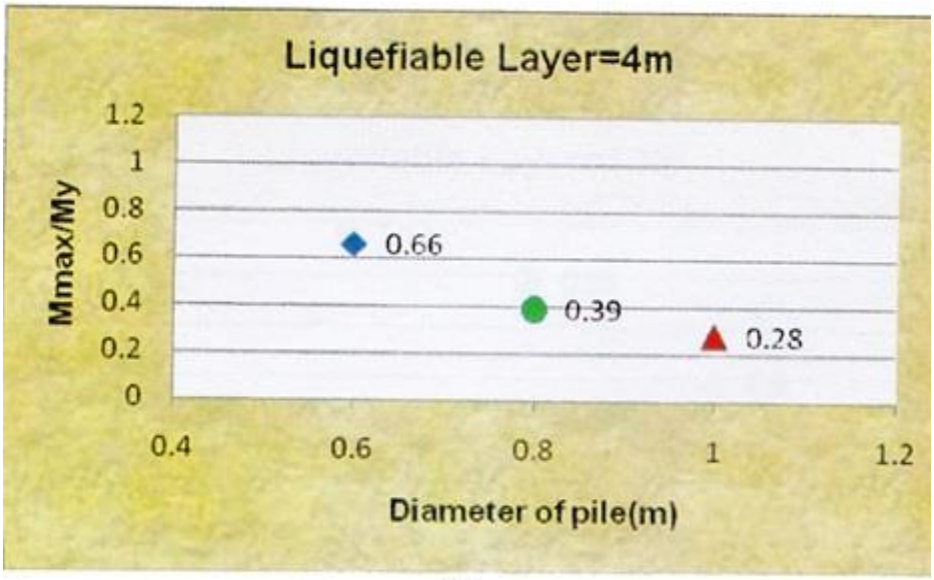
Table 5- The maximum bending moment of piles (MN.M)

LL D	0.6M	0.8M	1M
4M	0.156	0.220	0.312
6M	0.349	0.512	0.718
8M	0.427	0.706	1.260
10M	0.278	0.550	0.670

Investigating the bending failure mechanism of the pile

Among the models of pile failure in liquefiable soil, this section investigates only the bending failure of the pile. Therefore, if the maximum bending moment on the pile exceeds the yield moment of the pile section, it can be said that the pile has broken due to bending. Table (8) present the yield moments of pile sections for different pile diameters. Bending failure occurs when the maximum bending moment (M max)/ the yield moment of the pile section (My) ratio exceeds 1. Figure (9) shows the effects of changes in the pile diameter and the liquefiable layer thickness on the bending failure mode of the pile [7].

As seen in Figure (9), with this maximum acceleration of the earthquake, the pile with a diameter of 0.6 m will not break due to bending, only in the liquefiable layer thickness of 4 m with the maximum bending moment of 0.156 mega newton meters and the yield moment of 0.237 meganewton meters (i.e. M max/ My ratio of 0.66) and it will break in other thicknesses. Moreover, piles with a diameter of 0.8 m or 1 m will not break in all liquefiable layer thicknesses, except for the critical liquefiable layer thickness of 8 m. So, it is suggested to choose a larger pile diameter.



(A)

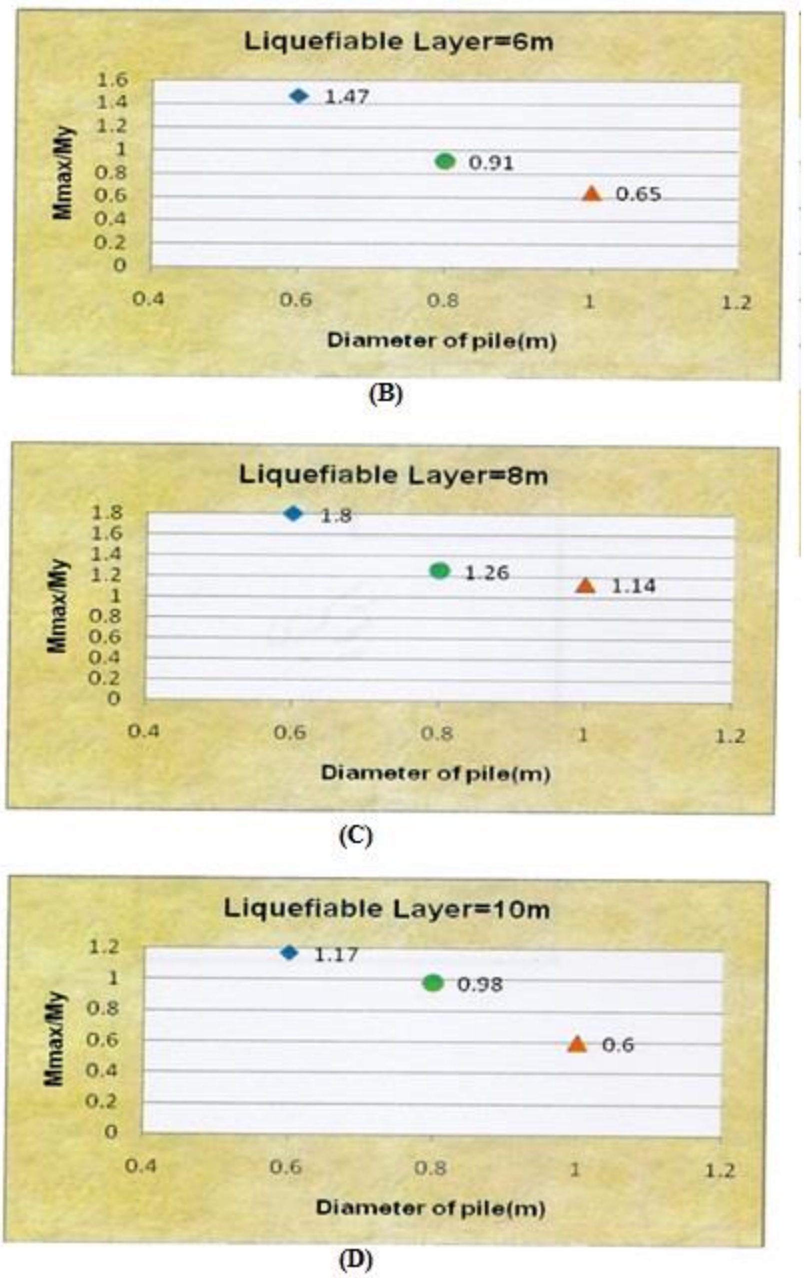


Figure 9- Variations in the M max / My ratio relative to pile diameter and different liquefiable layer thickness

Conclusion

According to numerical modeling carried out using the FLAC 2D software, the results of the present study are summarized as follows:

- The maximum horizontal displacement occurs at the pile head and in the elastoplastic zone. An increase in the liquefiable layer thickness resulted in the transfer of the maximum displacement to the plastic zone and it is obtained at the end of the earthquake.
- The horizontal displacement of the pile head increases with an increase in the liquefiable layer thickness, and this increase is greater for piles with a smaller diameter.
- One can see that with the increase in the liquefiable layer thickness up to 8 ms, the increase in horizontal displacement follows a slow trend while increasing the thickness from 8 to 10 m is accompanied by a sharper upward trend because the reduction in the depth of fixity of the pile results in the increased lateral pressure of the liquefiable soil on the pile.
- If the depth of the liquefiable layer is high, increasing the pile diameter will be significantly helpful in reducing the lateral displacement.
- The maximum bending moment on a pile with a free head, regardless of the liquefiable layer thickness, occurs at the boundary between the liquefiable and non-liquefiable layers.

- As the pile diameter increases, the maximum bending moment increases more quickly because its stiffness increases and the stiffness is directly related to the moment.
- It seems that in these soil-pile states, the liquefiable layer thickness of 8 m will be the critical thickness for the moment because the maximum bending is created at this depth.
- Increasing the pile diameter plays a significant role in keeping it safe from failure because with the increase in pile diameter, the moment of inertia of the pile enhances, and consequently, its strength increases.

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