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Numerical Evaluation of Pile Group Behavior Subject to Earthquake Loads

Ahmed Salman Jawad [1],*, **Bushra S. Albusoda**[2]

Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
a.jawad1901p@coeng.uobaghdad.edu.iq[1], dr.bushra_albusoda@coeng.uobaghdad.edu.iq[2]

ABSTRACT

The seismic design of pile foundations mainly relies on analyzing the seismic response of layered, liquefiable locations. Two design scenarios are taken into consideration from the case histories; the first is how pile foundations react to the stresses and lateral displacements brought on by the lateral dispersion of liquefied soil. The second is how to piles reaction to seismic activity that occurs with the development of high pore water pressures. The PLAXIS 3D software is utilized in this research with a non-linear soil constitutive model (hypoplastic model) for both dry and saturated loose sandy soils under the impact of two earthquakes and the motion of different features to give a complete understanding of the dynamic piled foundation response. The findings from this study show that the site profile, pile diameter, pile length, and excitation of ground motion significantly affect the dynamic response of the layered liquefied site. So, in the saturated case, the increase in the piles length to (L/D = 55) in comparison to the original length (L/D = 35) decreased the peak acceleration at the raft foundation by about (24.4 and 41.9) % under the effect of Kobe and Upland earthquake motion, respectively, while in the dry case, the reduction in peak acceleration was about (22.8 and 40.9) % under the effect of Kobe and Upland earthquake motion, respectively.

Keywords: Constitutive modeling, Hypoplasticity, Piles, PLAXIS 3D Software, Earthquakes.

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*Corresponding author

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التقييم العددي لسلوك مجموعة الركائز المعرضة لأحمال الزلزال

احمد سلمان جواد*، بشرى سهيل البوسودة

قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

يعتمد التصميم الزلزالي لأسس الركائز بشكل أساسي على تحليل الاستجابة الزلزالية للمواقع ذات الطبقات والقابلة للتسييل. هناك مساريين للتصميم يمكن ان ياخذ بنظر الاعتبار من الدراسات السابقة؛ المسار الأول هو كيف تتفاعل أسس الركائز مع الضغوط والازاحات الجانبية الناجمة عن الانتشار الجانبي للتربة القابلة للتسييل في حين المسار الثاني يتعلق بكيفية الاستجابة الزلزالية للركائز للحركة الشديدة التي تحدث مع تطور ضغط ماء المسام. تم استخدام برنامج PLAXIS 3D في هذا البحث مع النموذج التكويني غير الخطي للتربة (نموذج نقص اللدونة) لكل من التربة القابلة للتسييل وغير القابلة للتسييل تحت تأثير حركة زلزالين بميزات مختلفة لإعطاء فهم كامل لاستجابة الديناميكية التفاعلية بين التربة والركائز. تظهر النتائج من هذه الدراسة ان قطر وطول الركيزة وسعة الاهتزاز تؤثر بشكل كبير على الاستجابة الديناميكية لمواقع ذو الطبقات القابلة للتسييل. وبناءً على ذلك ، في الحالة التربة ذات مسامات مملوؤة كليا بالماء ، تؤدي الزيادة في طول الركائز إلى (L/D = 55) مقارنة بالطول الأصلي (L/D=35) إلى تقليل التسارع الاقصى في الاسس بحوالي (24.4 و 41.9) ٪ تحت تأثير حركة زلازل كوبي وأبلاند على التوالي ، بينما في الحالة التربة الجافة يكون الانخفاض في تسارع الاقصى حوالي (22.8 و 40.9)٪ تحت تأثير حركة زلازل كوبي وأبلاند على التوالي.

الكلمات المفتاحية: النموذج التكويني ، نقص المرونة ، ركائز ، برنامج PLAXIS 3D ، الزلازل.

1. INTRODUCTION

Liquefaction has been identified as the primary cause of destruction in both aboveground and underground structures during earthquakes, making it essential and complicated topics in geotechnical aspects **(Albusoda, 2016; Al-Taie and Albusoda, 2019; Sadiq and Albusoda, 2020; Hadi and Mekkiyah, 2023)**. Numerous recent earthquakes, including those in Kamchatka in 2006, Niigata in 1964, Kobe in 1995, Armenia in 1988, and Niigata in 1964, have offered numerous examples of devastation brought on by liquefaction **(Ter-Martirosyan and Anh, 2020)**.

The pore pressure that builds up in saturated sandy layers under the effect of seismic motion, that result from the liquefaction, significantly reduces the strength of those soils. This decrease in soil strength negatively affects bearing capacity and foundation settlements. So, in seismically active zones, pile foundations and supporting structures are frequently employed to address these issues **(Albusoda and Alsaddi, 2017; López Jiménez et al., 2019; Hama Salih et al., 2020; Abdul Hussein et al., 2021; Fattah et al., 2020 and Fattah et al., 2021).**

The response of pile foundation under the earthquake in the multilayered ground of two or more layers with different material properties is a sophisticated soil–pile reaction phenomenon that impacts the stability of piles and structures due to seismic waves tending to amplify and pass through the piled foundation to the structure as its move from harder to weaker soil layers close to the surface. As a result, structural oscillations are created and exert inertial loadings on the piled foundation. If the inertial load becomes high, pilings may suffer from significant lateral movement and moment. Therefore, in such locations, proper design for foundations is necessary **(Sica et al., 2013; Chatterjee et al., 2015; Lombardi and Bhattacharya, 2016. and Song et al., 2022)**.

Numerous numerical investigations have utilized the different constitutive models to comprehend the complicated seismic soil pile structure interaction during earthquakes.

(Wang et al., 2016) performed finite difference analysis on a soil model comprised of a single pile in saturated sandy layers based on the Opensess software using a unified plasticity model. The soil model consists of dense soil with a relative density (R.D=80%) overlaid on saturated sand with (R.D=30%). After being validated by centrifuge shaking table testing, the findings of this work were applied to examine the seismic performance of piles before and after liquefaction under monotonic and cyclic loads. **(Ramirez et al., 2018)** present a numerical investigation on non-linear dynamic site response of layered saturated sandy soil using two constitutive models.

The finite element results were verified using measured results from model tests. Also, it was demonstrated that the computed effects of vertical settlement, peak ground acceleration, and pore water ratio pressure meet those produced from two constitutive models. **(Limnaiou and Papadimitriou, 2022)** a numerical analysis was performed to examine the non-linear dynamic site response using the new model (Bounding surface plasticity, SANISAND-R) and applied to the finite difference software FLAC. The model input parameters were validated through numerical simulation of the experimental tests on sand samples. Then, the study uses the same set of model parameter values to determine the model's capability through comparisons with results from eight dynamic centrifuge experiments conducted on the same sand. Also, a case study was conducted to investigate the impact of the variation of the coefficient of permeability and the amplitude of earthquake motions on liquefaction behavior. **(Shen et al., 2022)** conducted finite difference dynamic analysis of a multi-layer liquefiable site using the OpenSees software under the effects of two earthquake motions (Kobe and El-Centro). Two constitutive models were applied. This study uses the PM4S model for sandy soils, whereas the plasticity model is used for crust clay for both liquefied and non-liquefied conditions.

Finally, the site response was investigated using a soil model of dimensions (50x21) m as a case study. It was concluded from this study that the saturated soil layer can amplify the peak ground acceleration and produce an increase in vertical settlement of about 40%.

2. VALIDATION PROBLEM

The findings of the experimental and numerical (PLAXIS 3D software) results were compared in this research to check the program's skills for analyzing the soil-pile interaction problem. The problem includes comparing the results obtained from published work carried out by **(Hussein and Albusoda, 2021)**, which provides for performing several shaking table tests and numerical simulations using ABAQUS software, and the results obtained from software. The soil profile consisting of loosely sandy soil with a (R.D=30%) and a thickness of 0.22 m supports a densely sandy soil with (R.D=70%) and a thickness of 0.58 m, as illustrated in **Fig. 1**.

2.1 Numerical Modeling

The numerical simulation is modeled under PLAXIS 3D software. It is consistent with that used in model work, as seen in **Fig. 2.**

2.2 Soil Modeling

The simple model (Mohr-Coulomb) was used in this investigation to replicate the material response of sand, and the required inputs of the model implementation were determined by **(Hussein and Albusoda, 2021)**, as illustrated in **Table 1**.

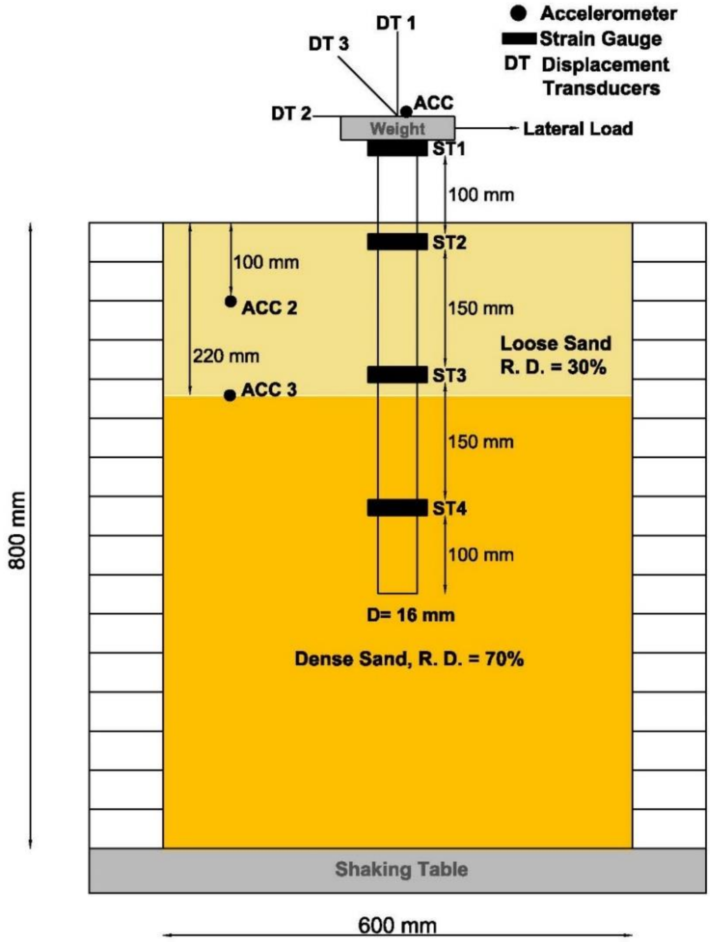


Figure 1. Soil and equipment arrangement **(Hussein and Albusoda, 2021)**

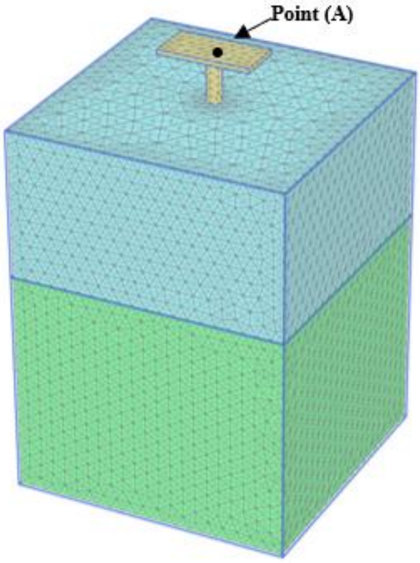


Figure 2. Finite element model

Table. 1 Parameter of the Mohr-Coulomb model **(Hussein and Albusoda, 2021)**

Parameter	Value
Specific gravity, Gs	2.64
Maximum void ratio, emax	0.86
Minimum void ratio, emin	0.66
The angle of internal friction φ	32° (loose), 35° (dense)
Young Modulus, E	10000 kPa
Poisson ratio, ν	0.33
Damping Ratio, ξ	5%

2.3 Comparison between Results

Comparisons between experimental test results and software findings are illustrated in **Figs. 3-5**. It can be noticed that the maximum settlement, lateral displacement, and acceleration at point (A) of the pile cap are very consistent between model and numerical analytical results. Based on that, the PLAXIS 3D program is believed to be a good tool for analyzing the effects of soil pile respone and is effective for exploring dynamic analysis with great accuracy.

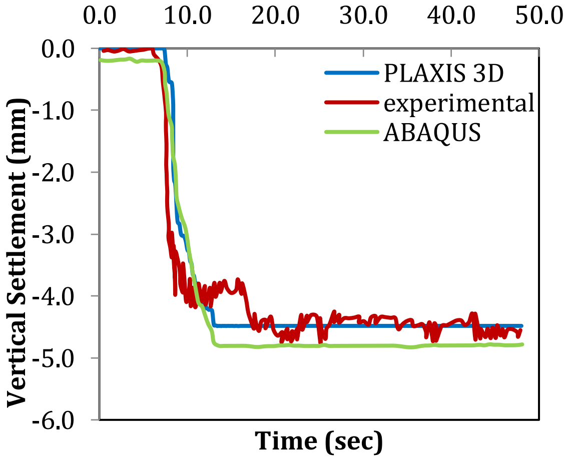


Figure 3. Change of vertical settlement with time at site (A) during Kobe earthquake

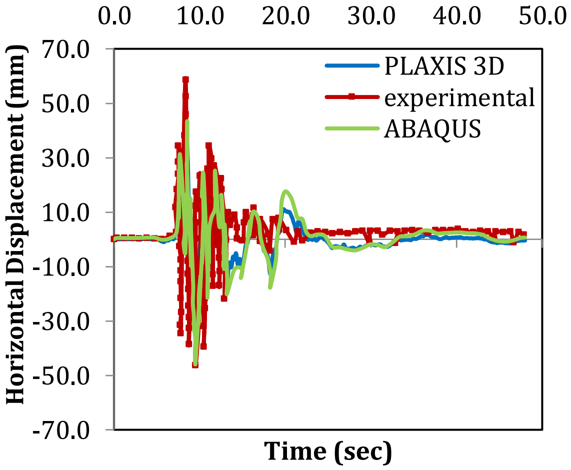


Figure 4. Change of Horizontal displacement with time at site (A) during Kobe earthquake

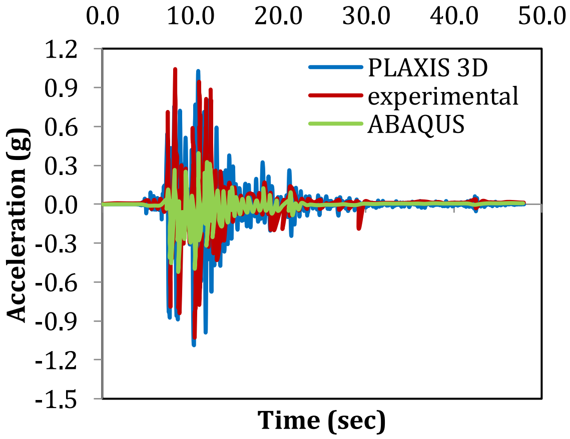


Figure 5. Change of Acceleration with time at site (A) during Kobe earthquake

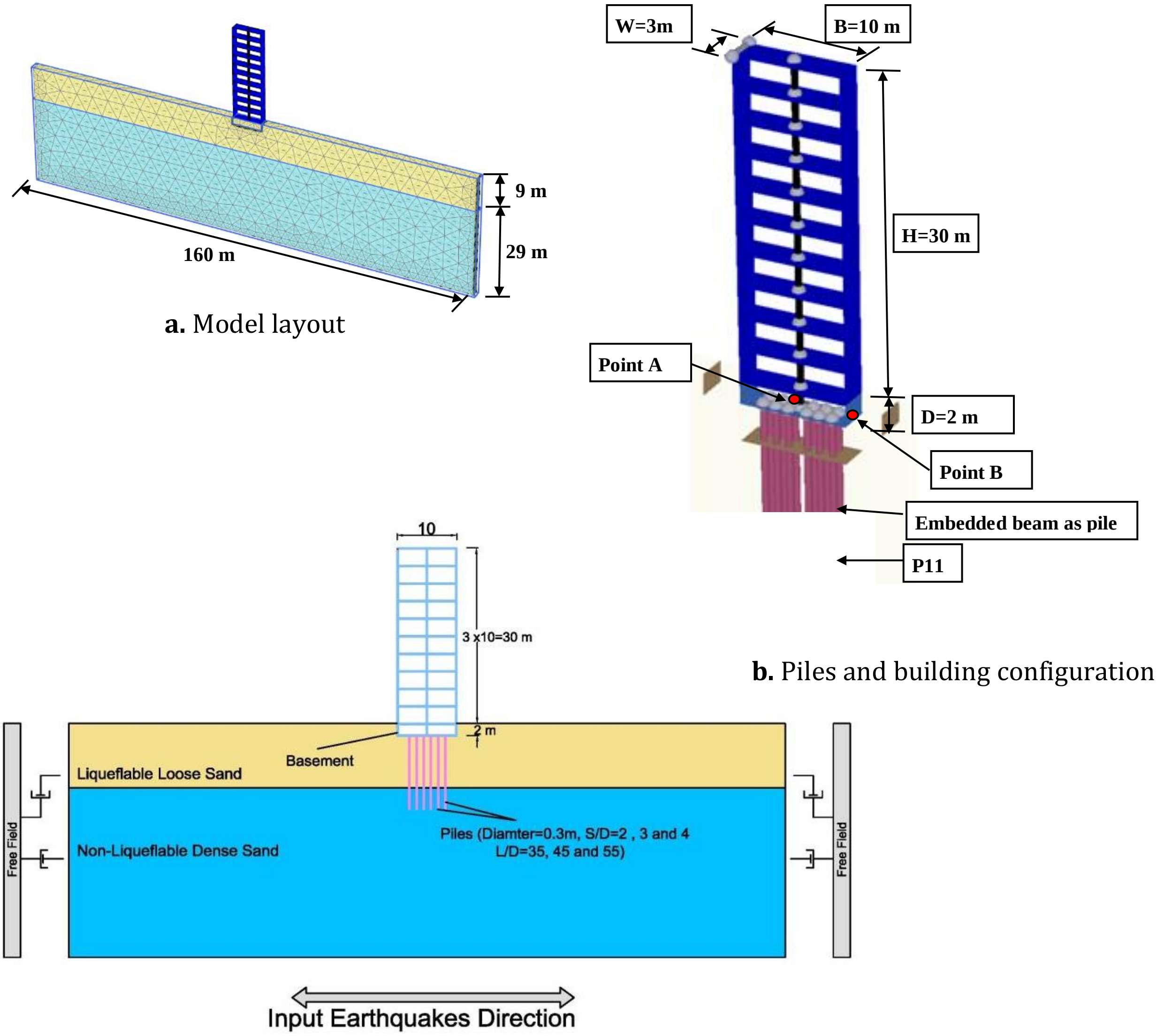
3. PARAMETRIC STUDY

A numerical study was conducted using the PLAXIS 3D on the pile-raft system for 2x12 pile configurations with different pile spacing and lengths, as shown in **Fig. 6a**. to have a deeper comprehension of the impact of different factors on the behavior of piles under seismic stress, two analyses were conducted: one with a saturated layered soil model of loose sand at the top 9 m and a stiff sandy soil at the bottom, and the other of a dry layered soil model as shown in **Fig. 6**.

3.1 Soil Constitutive Model

In the numerical analysis, selecting a constitutive model that can accurately represent the behavior of saturated soils is important. Thus, to examine the dynamic response of pile foundation exert to seismic stress, several researchers have presented numerical analysis with various constitutive models **(Dafalias and Manzari, 2004; Boulanger and Ziotopoulou, 2015)**.

In this work, the dynamic behavior of dense and loose sand layers is described using the hypoplasticity model created by **(Kolymbas, 1985)** and the parameters of the sand are illustrated in **Table 2**.



a. Model layout

b. Piles and building configuration

c. Front view of piles and building

Figure 6. 3D Finite element model

Table 2. Hypoplasticity Model Parameters Values Used in This Research **(Jawad and Albusoda, 2022).**

e_{d0}	e_{c0}	e_{i0}	α	β	n	h_s(GPa)
0.56	0.87	1.044	0.166	1	0.419	4

3.2 Earthquake Data

Two acceleration records, namely Kobe and Upland earthquakes, were utilized to explore the impacts of acceleration features inside soil and pile. The data for each seismic record is shown in **Fig. 7**.

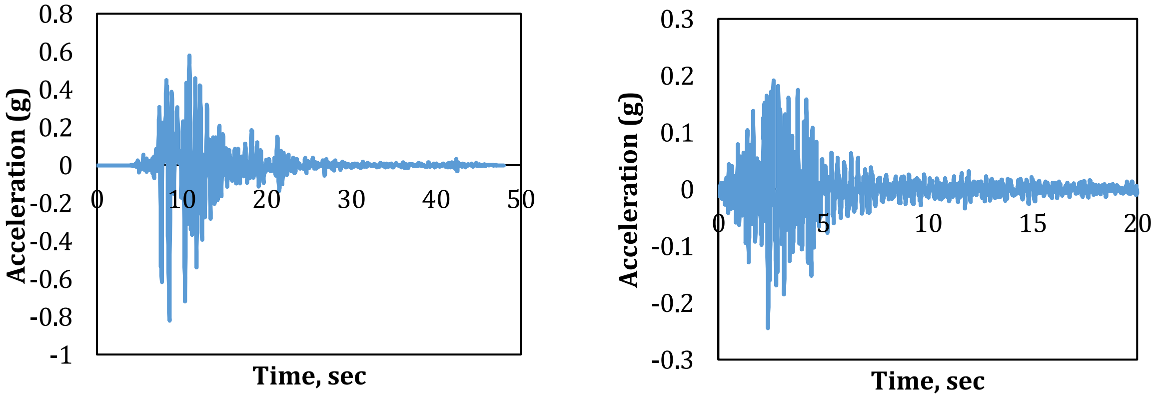


Figure 7. Earthquake record (a) Kobe, and (b) Upland **(Virtual Data Center (VDC)).**

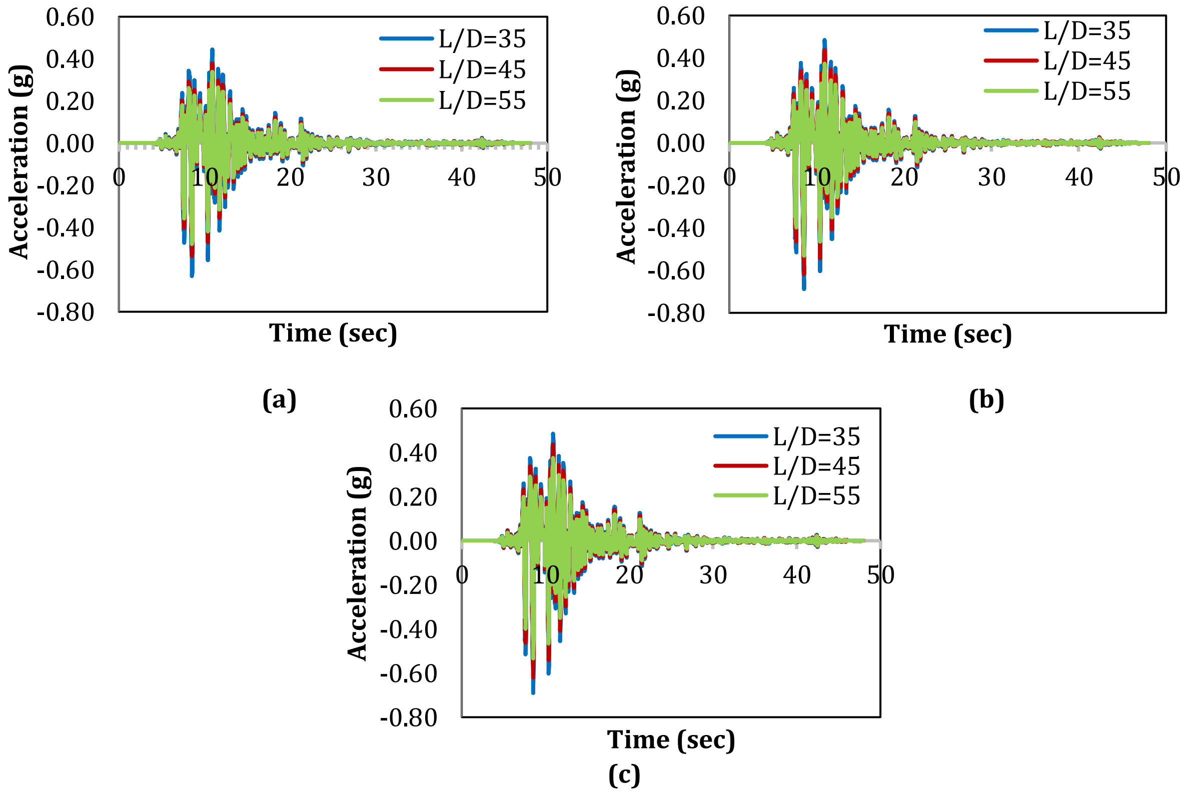
4. OUTCOMES AND INTERPRETATIONS

4.1 Effect of Piles Length and Piles Spacing on Peak Ground Acceleration

Many variables, including length, spacing between piles, and the earthquake's amplitude, are investigated on the response of piled foundation during an earthquake for both saturated (degree of saturation=100%) and dry state. The variation of horizontal acceleration with time for the different pile lengths and spacing under the effect of two excitation motions are shown in **Figs. 8 to13**. It can be concluded from these figures the following points:

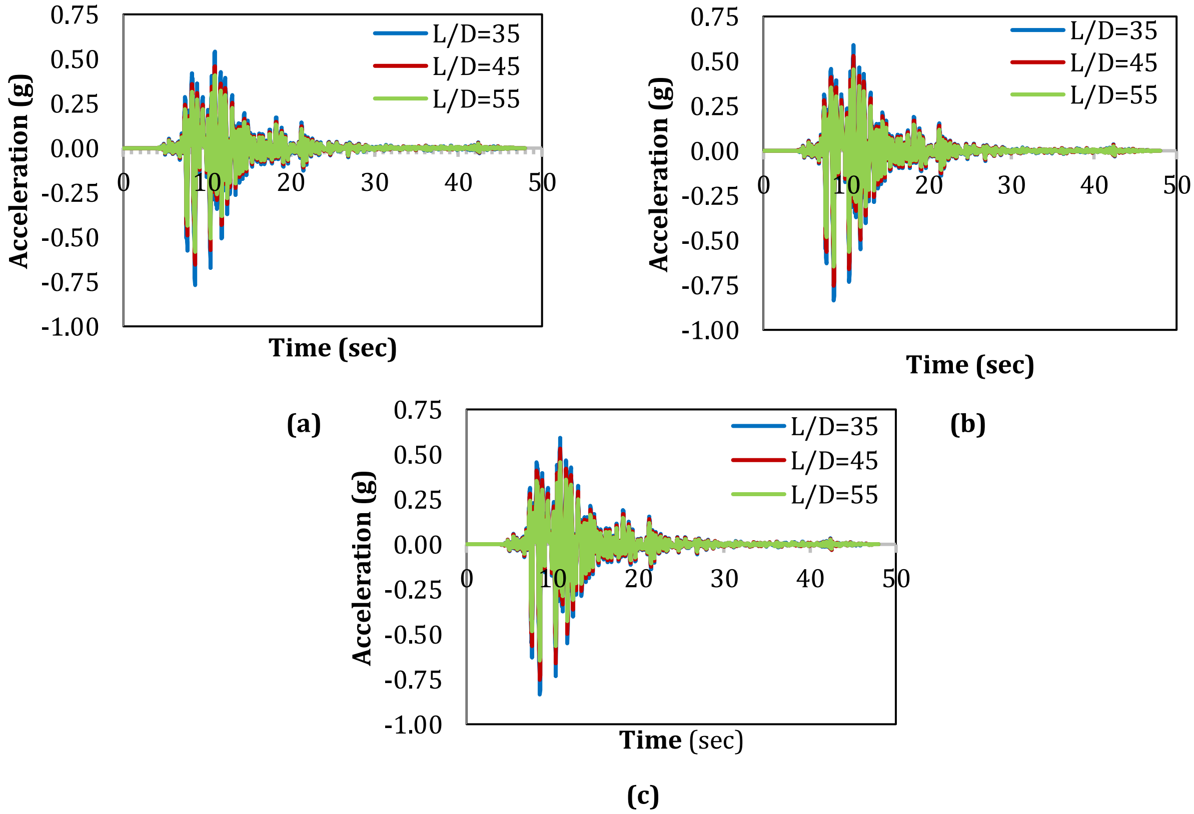
1. Significant amplification for each earthquake was observed in the seismic wave's transmission from the hard rock to the ground. The potential for an earthquake to damage the foundation system is increased by this amplification.
2. The time acceleration figures show how important soil type conditions are in changing the ground reaction. Additionally, compared to upland motion, Kobe motion is observed to have larger acceleration amplification.
3. The increase in pile length is accompanied by a decrease in peak ground acceleration due to the increased rigidity of the pile raft foundation. In contrast, the rise in pile spacing slightly increases the peak ground acceleration.

Many researchers have mentioned this behavior **(Matinmanesha and Asheghabadi, 2011; Liang et al., 2015; El-Attar, 2021; Al-Jeznawi et al., 2022 and Fansuri et al., 2022).**



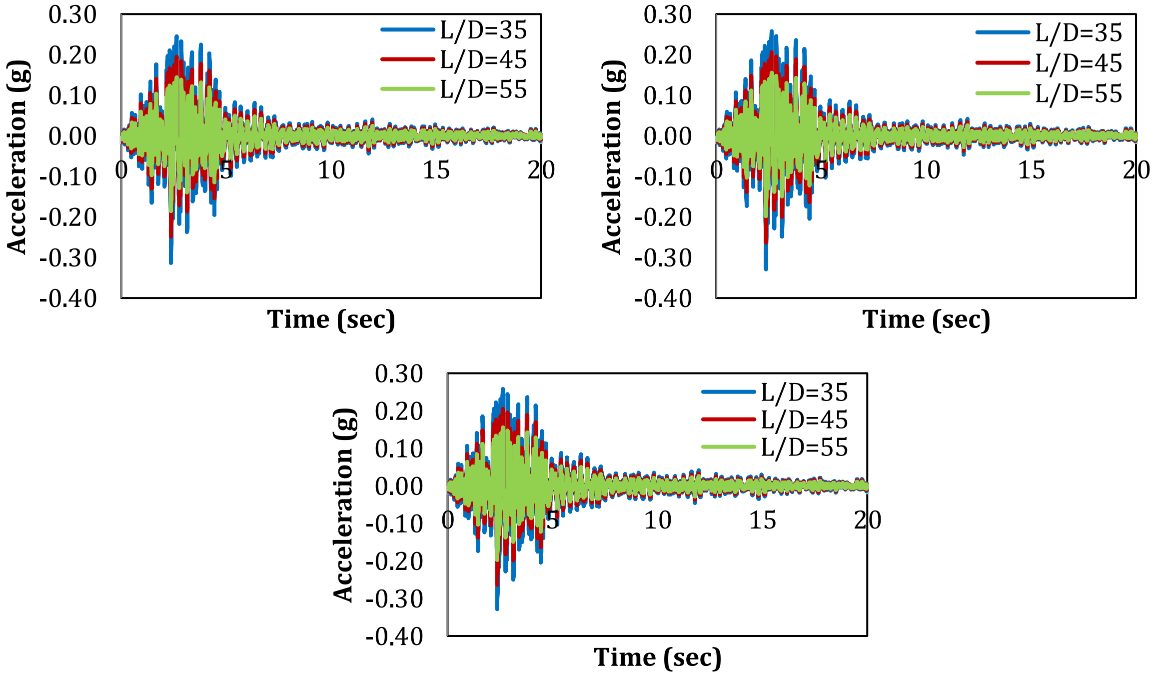
(a) (b) (c)

Figure 8. Variation of acceleration with time at the center of the raft during the Kobe earthquake for S/D (a) 2, (b) 3, and (c) 4 (dry state).



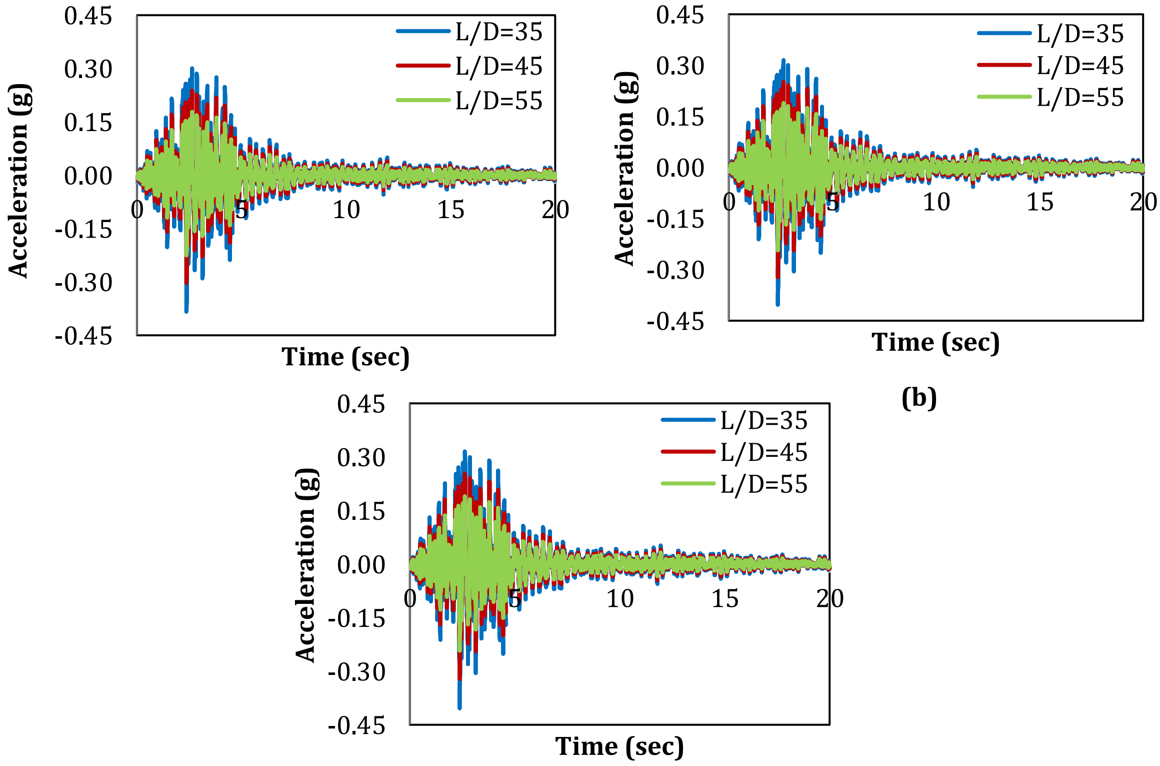
(a) (b) (c)

Figure 9. Variation of acceleration with time at the center of the raft during the Kobe earthquake for S/D (a) 2, (b) 3, and (c) 4 (saturated state)



(c)

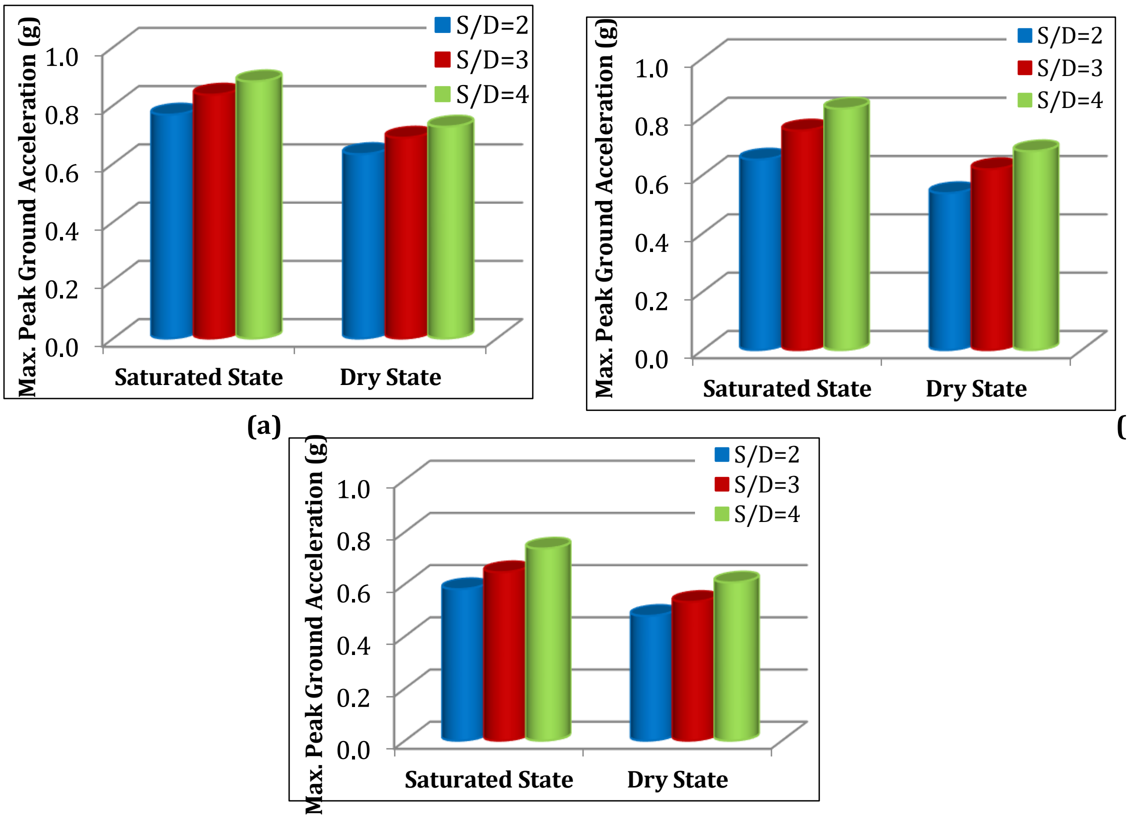
Figure 10. Variation of acceleration with time at the center of the raft during Upland earthquake for S/D (a) 2, (b) 3, and (c) 4 (dry state).



(b)

(c)

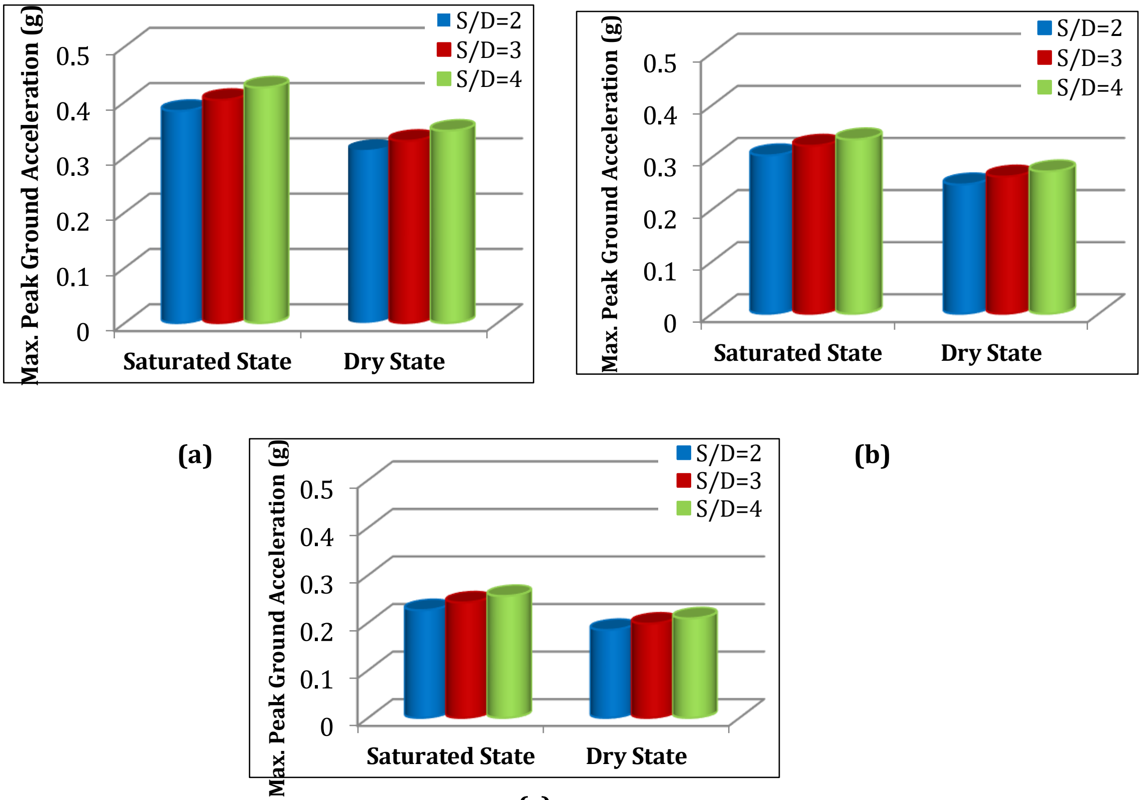
Figure 11. Variation of acceleration with time at the center of the raft during Upland earthquake for S/D (a) 2, (b) 3, and (c) 4 (saturated state).



(a) (b)

(c)

Figure 12. Variation of max. Peak ground acceleration with S/D at the center of the raft during the Kobe earthquake for L/D (a) 35, (b) 45, and (c) 55.



(a) (b)

(c)

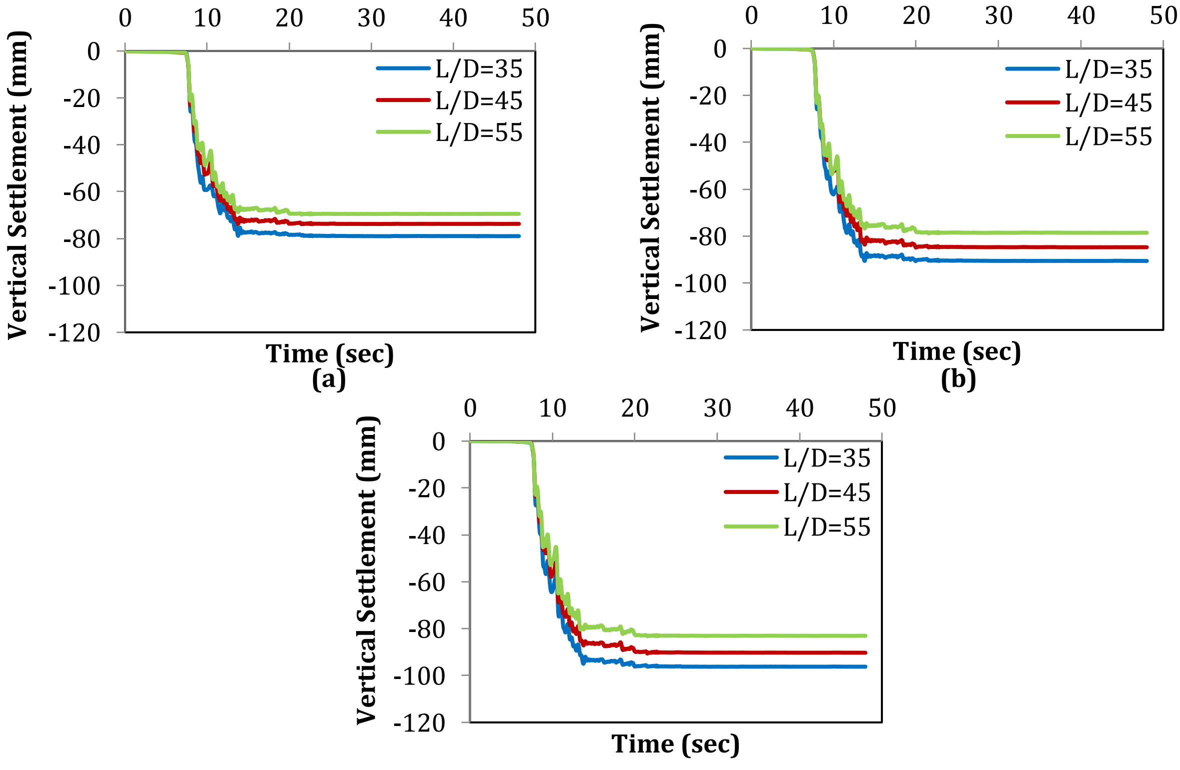
Figure 13. Variation of max. Peak ground acceleration with S/D at the center of the raft during Upland earthquake for L/D (a) 35, (b) 45, and (c) 55.

4.2 Effect of Piles Length and Piles Spacing on Vertical Settlement

The state of the soil greatly influences the behavior of a piled foundation system subjected to earthquake excitations. The piled foundation placed on two soil layers with varying densities and different pile lengths and spacing was numerically modeled to investigate the impact of water on soil structure interaction. The results obtained are shown in **Figs. (14-17)**. The figures refer to the variation of the total settlement of a piled foundation with time. Also, a comparison of two cases involved (dry state and saturation state) of two layers of sandy soil with different densities is made on the same figures to facilitate the comparison process. The differences in total settlement of the foundation between the two cases are noticeable. Whereas, the total settlement of the piled foundation system in the saturation state is greater than in the dry state for all pile lengths and spacing. The following points can justify this behavior:

1. The presence of water leads to decreased skin friction, which means reduced load resistance. As a result, the total settlement is increased. The skin friction decreases due to the soil's softening around the piles. In addition, the water works as a lubricant between the soil and piles.
2. The presence of water leads to liquefaction under the effects of earthquakes, increasing the total settlement. The effective stress of the soil is decreased due to pore water pressure generation.

This behavior was noticed by **(Tolun et al., 2020; Kwon and Yoo, 2020; Boyke and Nagao, 2022; Yu et al., 2022 and Nakagama et al., 2022).**



(c)

Figure 14. Variation of vertical settlement with time at point (A) during Kobe earthquake for S/D (a) 2, (b) 3, and (c) 4 (saturated state).

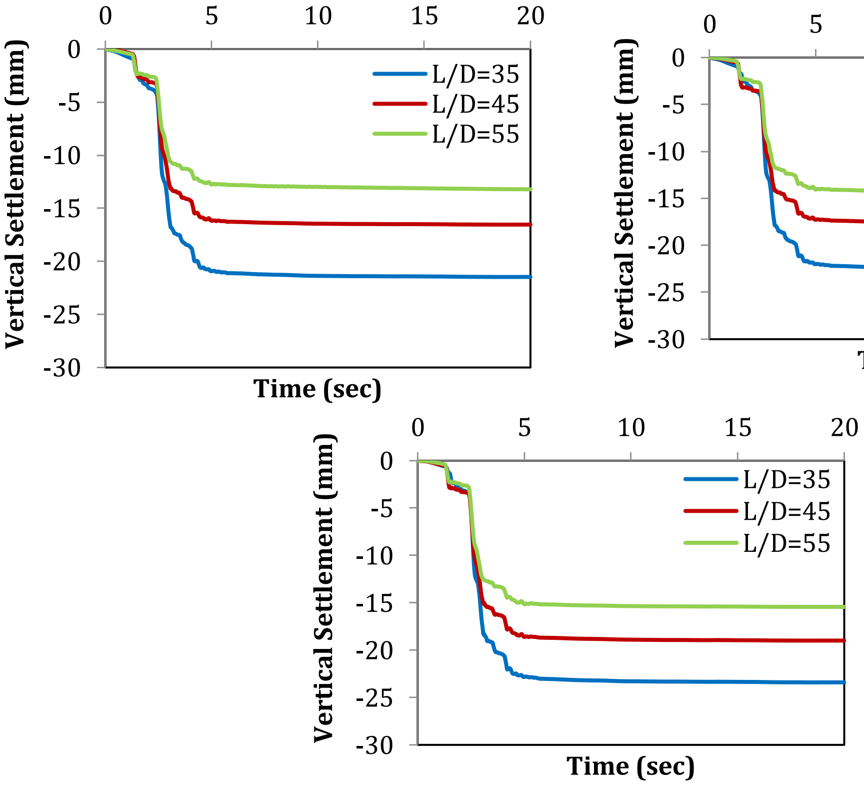
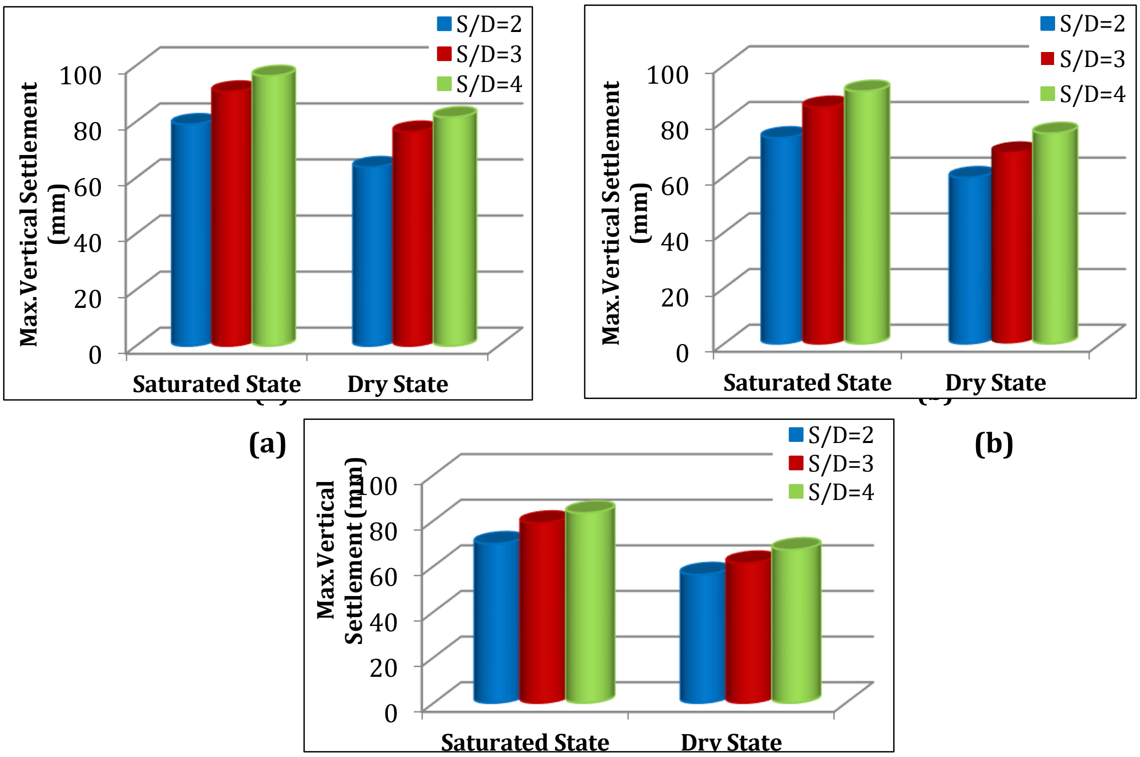


Figure 15. Variation of vertical settlement with time at point (A) during Upland earthquake for S/D (a) 2, (b) 3 and (c) 4 (saturated state).

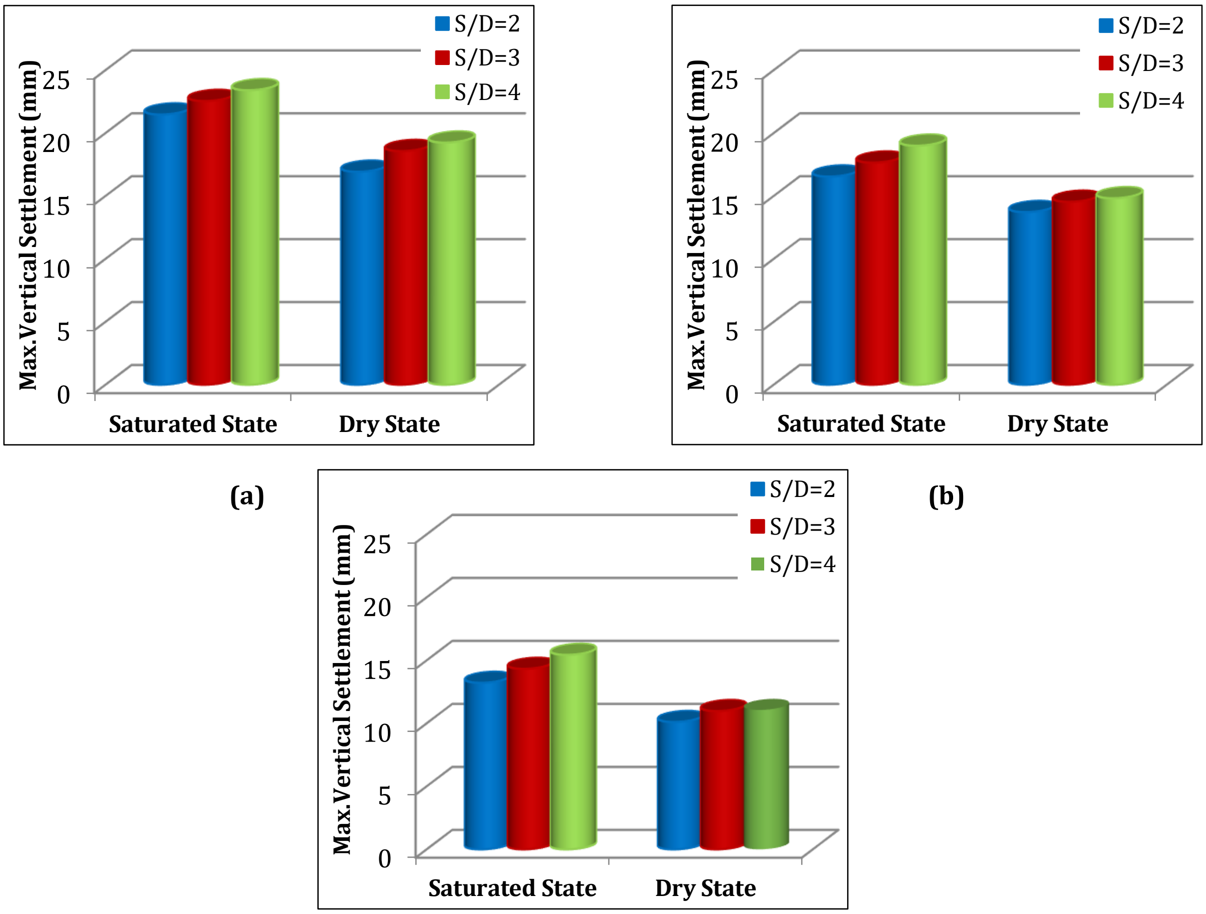


(a)

(b)

(c)

Figure 16. Variation of max. the settlement with S/D at point (A) during the Kobe earthquake for L/D (a) 35, (b) 45, and (c) 55.



(a) **(b)**

(c)

Figure 17. Variation of max. the settlement with S/D at point (A) during the Upland earthquake for L/D (a) 35, (b) 45, and (c) 55.

5. CONCLUSIONS

In the current work, a three-dimensional numerical analysis has been conducted utilizing the finite element computer program PLAXIS 3D to examine the dynamic response of the soil-pile system, which consists of a 2x12 pile group embedded in a two-layer stratum that is subject to the two earthquake motions, upland, and Kobe, that have been considered in the current study. The following major conclusions drawn from the numerical analysis are summarized as follows:

1. The peak acceleration developed at the center of the raft for non-liquefied soil is smaller than that for liquefied soil due to the degradation in stiffness of the soil, and as a result, a greater magnitude of lateral stress may be obtained from the seismic analyses.
2. In the saturated case, the increase in the length of piles to (L/D=55) in comparison to the original size (L/D=35) decreased the peak acceleration at raft foundation by about (24.4 and 41.9) % under the effect of Kobe and Upland earthquakes motion respectively, while in dry case the reduction in peak acceleration about (22.8 and 40.9) % under the impact of Kobe and Upland earthquakes motion respectively.
3. The increasing spacing between piles S/D from (3 to 4) compared to the original spacing (S/D =2) increases the peak acceleration by about (11.2 to 13.2) %, respectively, for saturated and dry conditions.
4. As pile length and spacing were increased, the total settlement dropped and increased, respectively. This behavior may have been brought on by a reduction in pile spacing, which acted as a confining medium and kept soil particles together. This behavior would have resulted in more lateral pressures, increased skin friction, and decreased settlements.

NOMENCLATURE

Symbol	Description	Symbol	Description
D	Pile diameter, m.	L	pile length, m.
e_{c0}	critical void ratio at zero pressure	n	exponent
e_{d0}	minimum void ratio at zero pressure	S	pile spacing, m.
e_{i0}	maximum void ratio at zero pressure	α	exponent
e_{max}	maximum void ratio	β	exponent
e_{min}	minimum void ratio	φ	angle of internal friction, deg.
E	stiffness modulus, kPa	ν	Poisson ratio
Gs	soil specific gravity	ξ	Damping ratio
hs	granulate hardness, GPa		

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Credit Authorship Contribution Statement
All the authors have read and approved the manuscript. The 1st author, Ahmed Salman Writing –the original draft of the manuscript. The 2nd author, Bushra Suhaile, reviewed and edited the manuscript.

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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