Finite Element Analysis of Raft Foundation on Various Soil Types under Earthquake Loading

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***Abstract*—**The design of shallow foundations to withstand different dynamic loads has given considerable attention in recent years. Dynamic loads may be due to the earthquakes, pile driving, blasting, water waves, and machine vibrations. But, predicting the behavior of shallow foundations during earthquakes remains a difficult task for geotechnical engineers. A database for dynamic and static parameters for different soils in seismic active zones in Iraq is prepared which has been collected from geophysical and geotechnical investigation works. Then, analysis of a typical 3-D soil-raft foundation system under earthquake loading is carried out using the database. And a parametric study has been carried out taking into consideration the influence of some parameters on the dynamic behavior of the raft foundation, such as raft stiffness, damping ratio as well as the influence of the earthquake acceleration-time records. The results of the parametric study show that the settlement caused by the earthquake can be decreased by about 72% with increasing the thickness from 0.5 m to 1.5 m. But, it has been noticed that reduction in the maximum bending moment by about 82% was predicted by decreasing the raft thickness from 1.5 m to 0.5 m in all sites model. Also, it has been observed that the maximum lateral displacement, the maximum vertical settlement and the maximum bending moment for damping ratio 0% is about 14%, 20%, and 18% higher than that for damping ratio 7.5%, respectively for all sites model.

***Keywords*—**Shallow foundation, seismic behavior, raft thickness, damping ratio.

I. Introduction

It is well known that the soil-foundation-superstructure system should act in a coherent way. In particular, if the project is influenced by high dynamic loadings (such as earthquakes), it is greatly desirable that the soil-foundation part should play a suitable role in delivering the required total performance. The dynamic bearing capacity problem for shallow foundations especially under earthquake loading has been attracting the attention of researchers for the last about sixty years. Shallow footings may be subject to decrease in capacity and an increase in leveling and tilt because of seismic loading as shown during many earthquakes. Examples of the failure of shallow foundations in Adapazari in Turkey due to the 1999 Kocaeli earthquake are shown in [1]. The shallow foundations should be safe and designed for all loads that included static and the dynamic loads imposed by the earthquake excitations. Earthquake-related ground shaking can affect the shallow foundation in a variety of ways [2]. In this study, the soil parameters for most Iraqi soils are evaluated and collected from different resources in order to be used as input data for studying behavior of shallow foundation under seismic waves by finite element grogram PLAXIS 3D 2013. The maximum lateral displacement of soil under foundation, the maximum vertical settlement of foundation and the maximum bending moment are determined, also the effects of raft thickness, damping ratio, and different earthquake excitation are investigated for the parametric study.

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II. Database for Seismic Analysis

In this study, the data used are for different soils in Iraq [3]. These data were based on geotechnical and geophysical site investigation reports for many projects in various sites of Iraq. The data are collected from different sources. The reports were for about 50 projects of water treatment plants and pumping stations, multi-story buildings, electrical substations, stadiums, oil refinery and others from different locations in Iraq. Moreover, the sites are grouped into nine regions based on the boundaries of Iraqi governorates. The zones with their site symbol are listed in Table I. In addition, these zones and projects locations in Iraq are shown in Figs. 1 and 2.

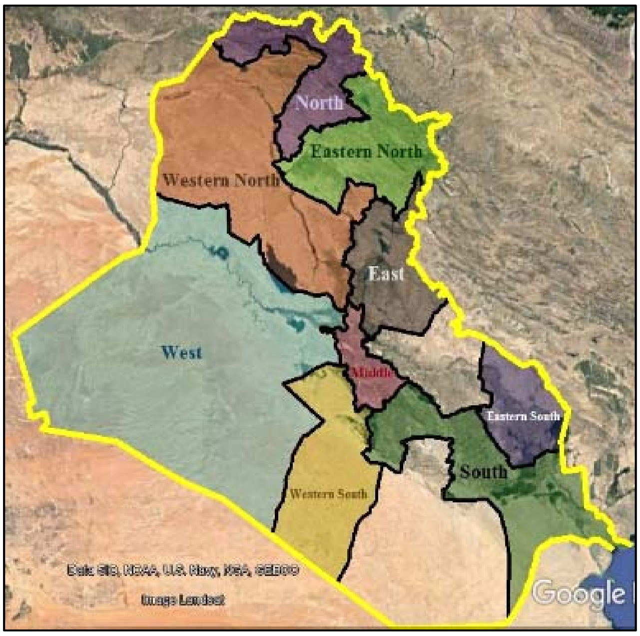


Fig. 1 Iraq seismic zones

TABLE I
IRAQ SEISMIC ZONES AND SITES SYMBOLS [3]

Zone	Site symbol	Governorate	Zone	Site symbol	Governorate
North	N1	Dohuk	Middle	M10	Babylon
	N2	Dohuk	East	E1	Diyala
	N3	Irbil		E2	Diyala
	N4	Irbil	West	W2	Anbar
Eastern North	EN1	Sulaymaniyah	Western south	WS1	Karbala
	EN2	Sulaymaniyah		WS2	Karbala
	EN3	Kirkuk		WS3	Karbala
	EN4	Kirkuk		WS4	Karbala
	EN5	Kirkuk		WS5	Najaf
	EN6	Kirkuk		WS6	Najaf
	EN7	Kirkuk	Eastern South	ES1	Missan
Western North	WN1	Mosul		ES2	Missan
	WN2	Mosul		ES3	Missan
	WN3	Mosul		ES4	Missan
	WN4	Salah Al-den	South	S1	Al Dewaniya
	WN5	Salah Al-den		S2	Al Dewaniya
Middle	M1	Baghdad		S3	Al Nasiriya
	M2	Baghdad		S4	Al Nasiriya
	M3	Baghdad		S5	Al Nasiriya
	M4	Baghdad		S6	Al Basrah
	M5	Baghdad		S7	Al Basrah
	M6	Baghdad		S8	Al Basrah
	M7	Baghdad		S9	Al Basrah
	M8	Baghdad		S10	Al Basrah
	M9	Babylon			

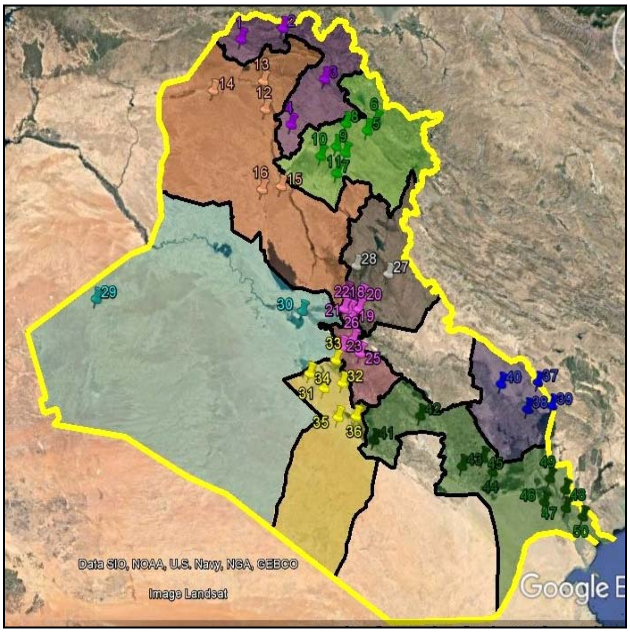


Fig. 2 Projects locations in Iraq

III. FINITE ELEMENT ANALYSES

Finite element analysis is carried out using PLAXIS 3D 2013 software depending on the Mohr Coulomb model. All the data necessary for the Mohr-Coulomb model were available. These parameters with their standard units are listed as [4]: E: Modulus of elasticity [kN/m^2], ϕ: Angle of internal friction [°], υ: Poisson's ratio [-], c: Cohesion [kN/m^2], ψ : Angle of dilatancy [°], γ_{sat}, γ_{unsat}: Saturated and Unsaturated unit weight respectively [kN/m^3].

The parameters for dynamic analysis used in PLAXIS 3D 2013 software are [4]: V_s: Shear wave velocity [m/s], V_p: Pressure wave velocity [m/s], E_d: Dynamic modulus of elasticity [kN/m^2], G_d: Dynamic shear modulus [kN/m^2].

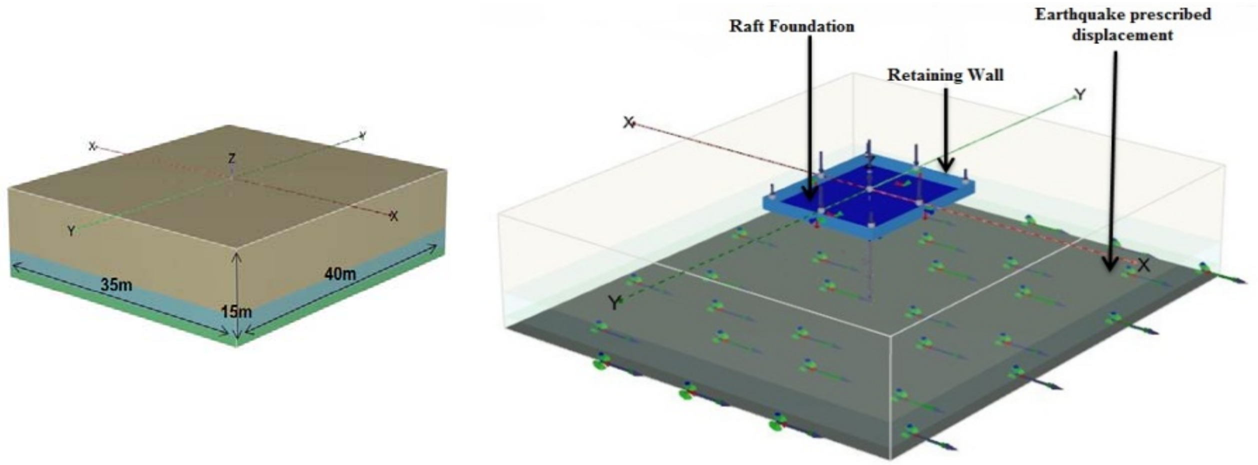
The dataset for soils parameters used in this study are given in [3].

IV. SEISMIC MODELING OF SHALLOW FOUNDATION ON VARIOUS SOIL TYPES

A. Geometry Model

A PLAXIS 3D 2013 model of a raft foundation 10 m×12 m×1 m embedded in a 35 m×40 m×15 m soil model is simulated in order to study the effect of earthquake on shallow foundation in most Iraqi soils. A typical geometry and soil layers model together with the raft foundation, point load and prescribed displacements are given in Figs. 3 (a) and (b). The model dimensions are: X=35 m, Y= 40 m, and Z=15 m.

For the structure model consisting of four-multi story building with a basement, the height of the basement is 2 m, and the height of each floors of the building is 3 m. The structure consists of flat plate slabs (without beams), columns, retaining walls and raft foundation with dimensions of 10 m×12 m×1 m. The structure and foundation are designed by program ETABS as shown in Fig. 4. Table II shows the properties for each structural element of the study.



(a) (b)

Fig. 3 (a) Geometry and soil layers model (b) Embedded raft foundation, point load and the prescribed displacement

TABLE II
PROPERTIES OF STRUCTURAL ELEMENTS

Properties	Units	Slabs	Column	Retaining walls	Foundation
Thickness	m	0.2	(0.5*0.4)	0.25	1
Concrete density	MPa	24	24	24	24
Yield strength of steel	kN/m^2	420	420	420	420
Compressive strength of concrete	kN/m^2	30	30	30	30
Young's modulus	MPa	24000	24000	24000	24000
Poisson's ratio	-	0.20	0.20	0.20	0.20

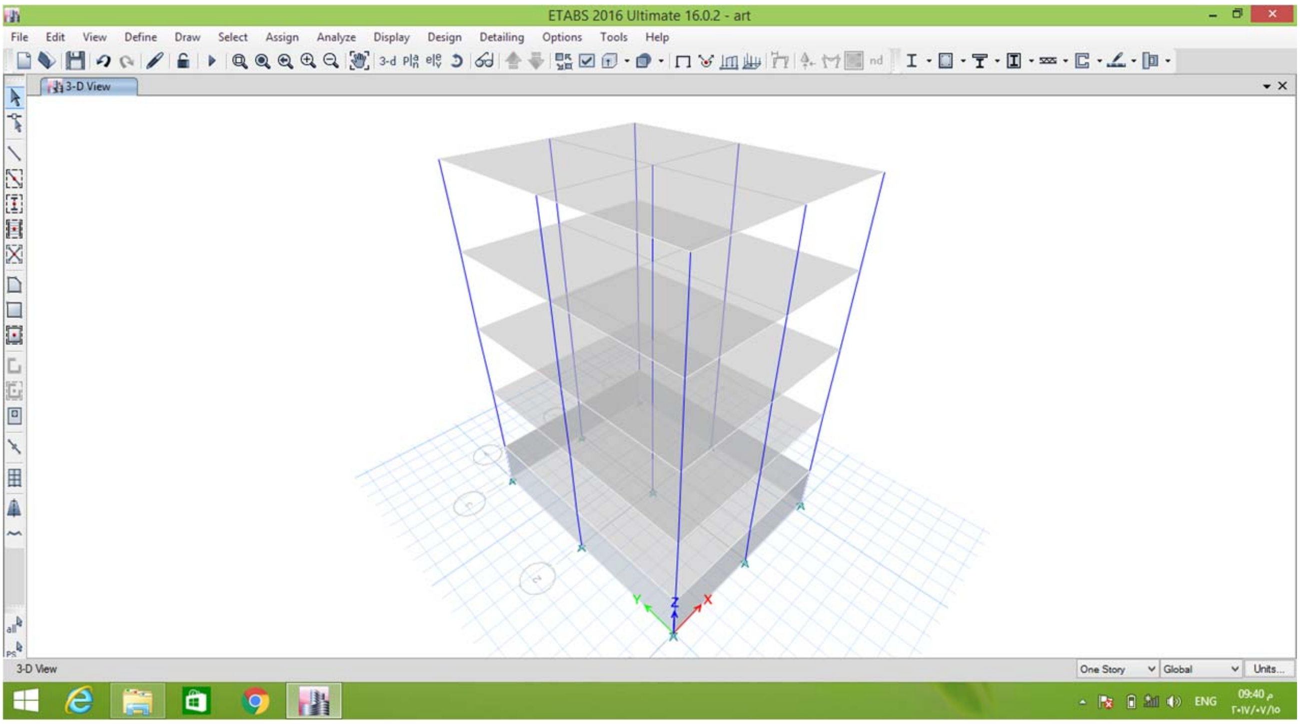


Fig. 4 The multi-story building

B. Soil Modeling

The Mohr-Coulomb (MC) model for soil is used in this study. The soil parameters that are used in MC model are geotechnical and geophysical properties, the geotechnical properties are (φ, c, γ_{wet} and γ_{dry}), and the geophysical properties are (V_s, V_p, G_d, E_d and v).

C. Earthquake Modeling

One of the highest earthquakes that hit Iraq was in Ali-AL-Ghrabi at Missan governorate as shown in Fig. 5 and is considered as input dynamic prescribed displacement applied at the bedrock level along the x- direction of the model in the form of acceleration-time readings in m/s^2 and s, respectively.

V. Influence of Soil Dynamic Parameters on the Behavior of Raft Foundation

The results indicate that the maximum lateral displacement in soils occurs at N4 site in North zone, EN4 in Eastern North zone, WN4 in Western North zone, M7 in Middle zone, W2 in West zone, E2 in East zone, WS6 in Western South zone, ES4 in Eastern South zone and S4 in South zone as shown in Fig. 6. The reasons why the maximum lateral displacements occur at these sites are that the soil layers below the foundation are most likely lean or fat clay (CL, CH) and some of them are contained soft and loose soils also may be due to the soil geophysical properties as the values for V_s and V_p in the clayey soil are lower than that for the sandy soil.

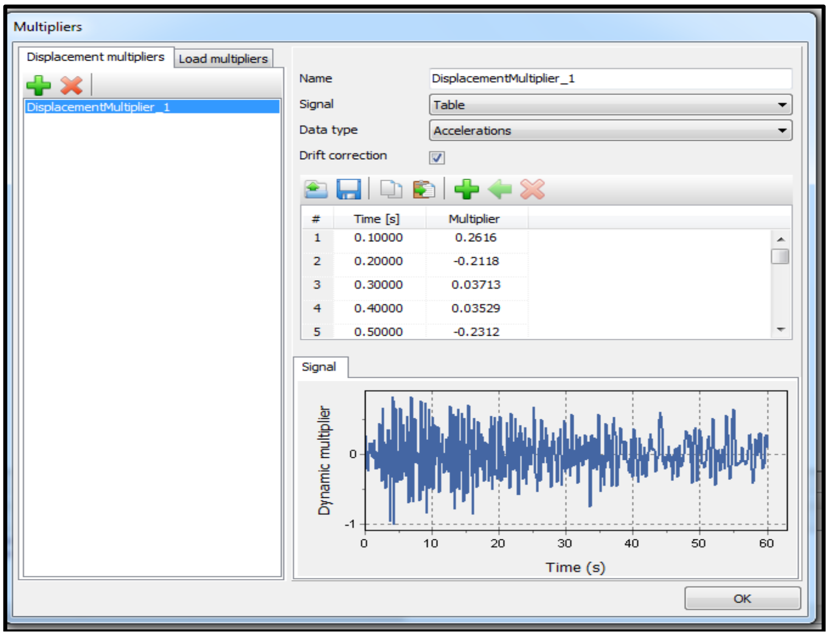


Fig. 5 Acceleration – time records of earthquake hit Ali Al-Gharbi

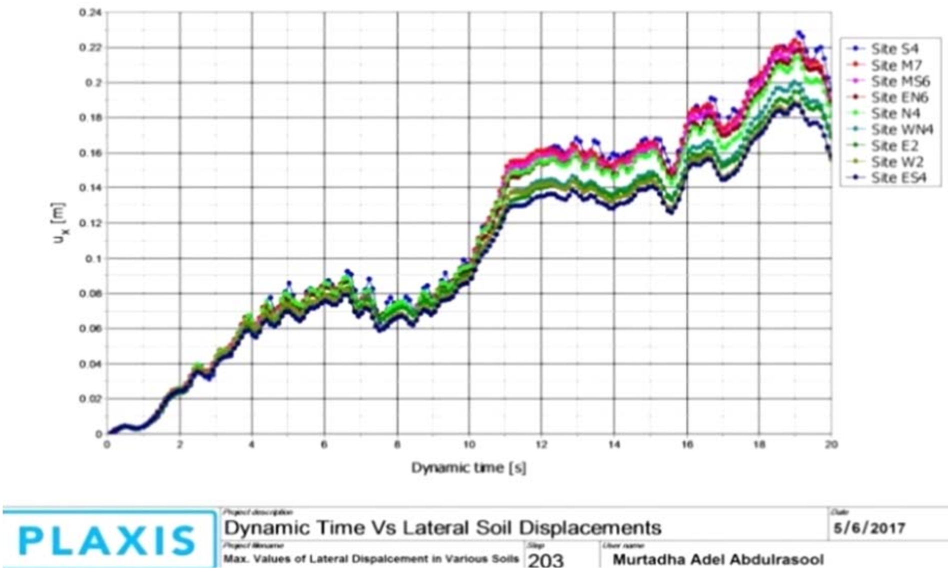


Fig. 6 Maximum lateral displacements in soils for Iraqi zones

The increase in the depth with soil layers caused higher values for both wave velocities and higher effective stresses, thus it can be concluded that V_p and V_s wave velocities are increased in proportion with soil strength and play a vital role for the results of lateral displacement in soils. Fig. 7 shows the lateral displacements of the raft foundation under earthquakes excitation for ten sites from the zones, it can be shown that the maximum value of displacement is 5.8 mm in S4 (South Zone). Also, the maximum value for lateral displacement in soil appeared in site S4 and the arrangement of ten sites for lateral displacement values in foundation are similar to the arrangement for that of lateral displacement value in soil. It can be indicated that the soil behavior under dynamic loads plays a vital role for effective on lateral displacement of foundation.

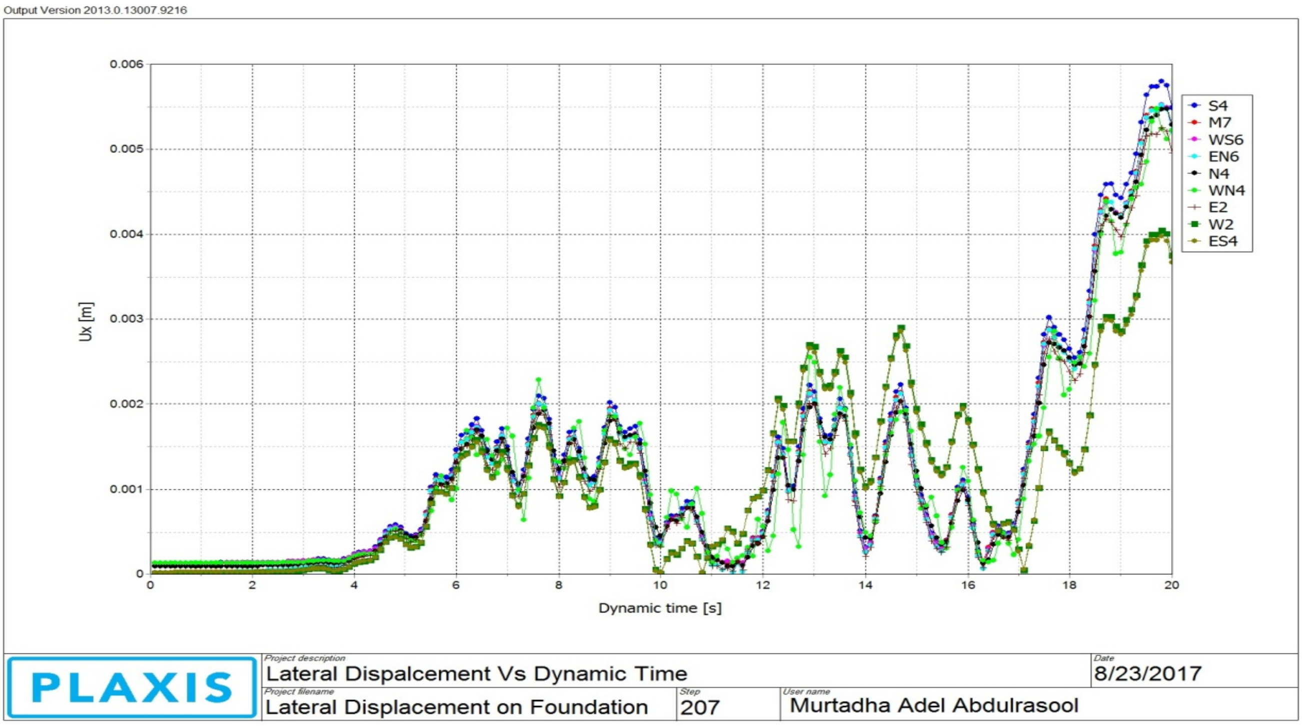


Fig. 7 Dynamic time vs lateral displacement on foundation

The settlement of foundation depends on the bearing capacity of soil. For the hard soil especially rock, the settlement has minimum value because of highly bearing capacity of hard soil, for the soft and loose soils, the settlement has maximum value because of low bearing capacity as shown in Fig. 8.

It can be indicated that the soil layers below the foundation predicting the larger lateral and vertical displacements are most likely lean or fat clay (CL, CH) with lower values of shear wave velocity. The S wave is considered one of the most affective and powerful in geotechnical soil properties [5]. Also, when the types of soil layers below foundation mostly contain saturated loose to medium sand (SP), larger lateral and vertical displacements mostly appear under earthquake action. When loose soil deposits have saturated, it displaces substantially with generation of large pore water pressure and eventually liquefies [2].

VI. Parametric Study

In order to progress and rise with raft foundation designed criteria under dynamic loading according to [6] the foundation should be designed to carry out the different structural loads (static loads) and should be designed to carry out the bending and displacement of the raft foundation results from generated dynamic loading. Designing of large raft foundations will need requirements different from that for strip or pad footings. As sliding may be possible for large raft foundation, rotational "failure" or bearing capacity is unlikely. Also, it may flex during earthquake loading and the seismic actions across the raft may become incoherent. Evaluation of such issues is unlikely to be required for most pads and strip footings designs [7].

Models of raft foundation embedded in a soil model for sites N4, EN6, WN4, M7, W2, E2, WS6, ES4 and S4 are chosen for the parametric study according to maximum lateral displacement that pronounced during earthquake excitations. All the models in this study that included soils, foundation, dynamic load, static point loads and mesh generation are calculated and simulated by using a finite element program PLAXIS 3D 2013.

A. Effect of Raft Thickness

The vertical settlement and the bending moment for different raft thickness (i.e., T=0.5 ,0.75,1,1.25,1.5 m) which is embedded in a soil models for sites N4, EN6, WN4, M7, W2, E2, WS6, ES4 and S4 are studied. The maximum value of vertical settlement occurred in lowest thickness of foundation as shown in Fig. 8. The maximum value of settlement was in WS6 at raft thickness (0.5 m) with a value of 30.6 mm, and the minimum value was 8.85 mm at site E2 at a raft thickness of 1.5 m. For the lateral displacement that happened in soil under raft foundation, the thickness of the raft has no effect on displacement since the lateral displacement of soils is affected only by changing the soil properties, changing the multiplier of the motions of earthquakes and varying the damping ratio.

The raft thickness relationship with the settlement is reverse. And it can be concluded that the large thickness could resist greatly the ultimate force, absorbed that loads applied by superstructure and highly resist the seismic load influence. Under seismic loads, it can be observed that the vertical settlement of foundation being higher when thickness was reduced. The displacement caused by seismic waves can be reduced by about 72% with increasing the thickness one and a half times as shown in the Fig. 8. Thus, the foundation must continue to support the structure during and after the seismic event and foundation deflections must remain within the range that the structure can withstand. In order to limit the transient deflection, it is very desirable that the stiffness of the combined building and foundation system does not cause the structure to respond within the peak frequency range of the seismic motion.

For the maximum bending moment that occurred at the raft foundation, the results predicted that the maximum value was at site S4 for which the soils are soft to medium clayey soil as shown in Fig. 9. This figure draws the maximum bending moment for different raft thickness (T_r= 0.5, 0.75,1, 1.25, 1.5 m) embedded in a model for sites N4, EN6, WN4, M7, W2, E2, WS6, ES4 and S4. It can be indicated that the maximum moment of a raft foundations is increased with increasing the raft thickness. The increase in thickness from 0.5 m to 1.5 m causes increasing in the maximum bending moment by about 455% in all sites model.

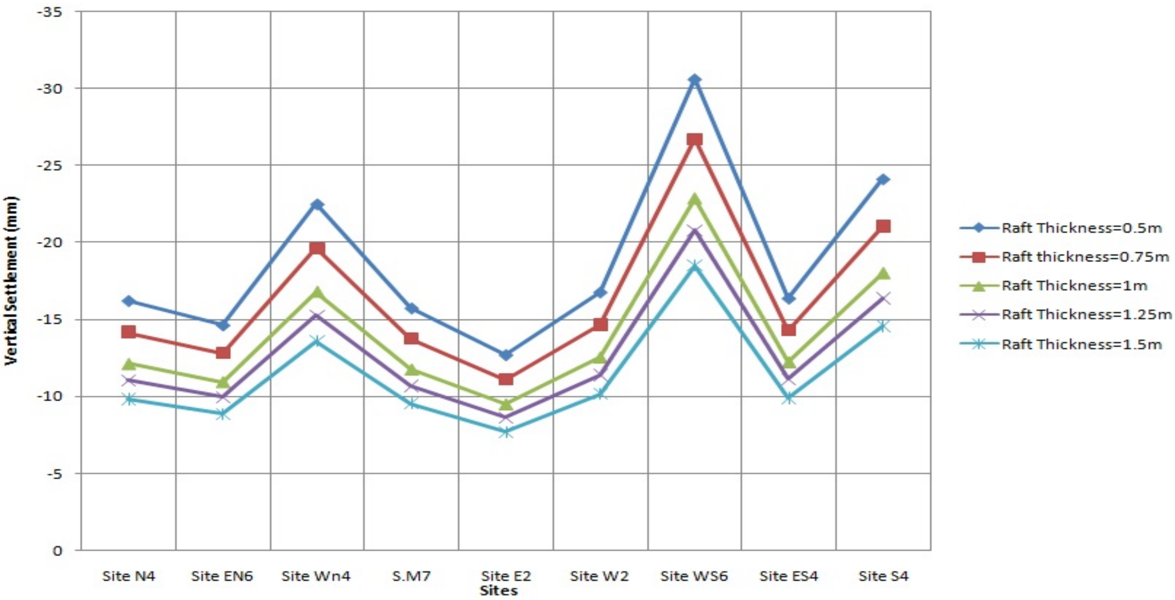


Fig. 8 Vertical settlement at raft foundation in different foundation thickness and different Sites

Fig. 9 Maximum moment at raft foundation for different foundation thickness and different sites

B. Effect of Different Earthquakes

Comparable to the movement of walls laterally under seismic effect, foundations will settle in a similar way in an earthquake as the acceleration ratio exceeds the critical value. Even at moderate acceleration levels, the cost of foundations designed to stay below this critical value and avoid seismic settlement may be excessive, and for larger earthquakes it may be prohibitive. In such cases, a displacement-governed design may be preferable or required [8].

To study the effect of most destructive earthquakes that have been happened years ago in various locations on the behavior of raft foundation using the model studied by PLAXIS 3D, El-Centro, Kobe and Tokyo earthquakes which are the most common earthquakes will be considered in the analyses. The 1940 El Centro earthquake had a local magnitude of 6.9 and a maximum perceived intensity of X (Extreme) on the Mercalli intensity scale, for the Kobe earthquake the latest hazard had been recorded in June 2015ML= 4.1 – 209 km SE of Shingu, Japan and for Tokyo earthquake, ML=5.2 was recorded 223 km from Ogasawara, Tokyo, Japan in June 2016. These earthquakes will be considered together with the Ali Al-Gharbi earthquake in south of Iraq with ML = 4.8 magnitude according to Richter scale. All the earthquakes simulation will be for site S4, and the input data of seismic waves are considered as time versus acceleration.

The results show a maximum value of lateral displacement under El-Centro earthquake and the minimum value under Kobe earthquake, it has been observed that the maximum lateral displacement for El-Centro earthquake is about 92% more than that Kobe earthquake for the same sites. This may be due to fact that the displacement depends on the local magnitude of the seismic wave and the peak ground acceleration which appears to be the highest at the El-Centro earthquake, also the results show the change in the behavior of lateral displacement for soils as shown in Fig. 10. In earthquakes, the accelerations are considered one of the most affective at dynamic model because the accelerations determined how much force the earthquake exerted on the building and the range of the accelerations are 0.05 to 1 g.

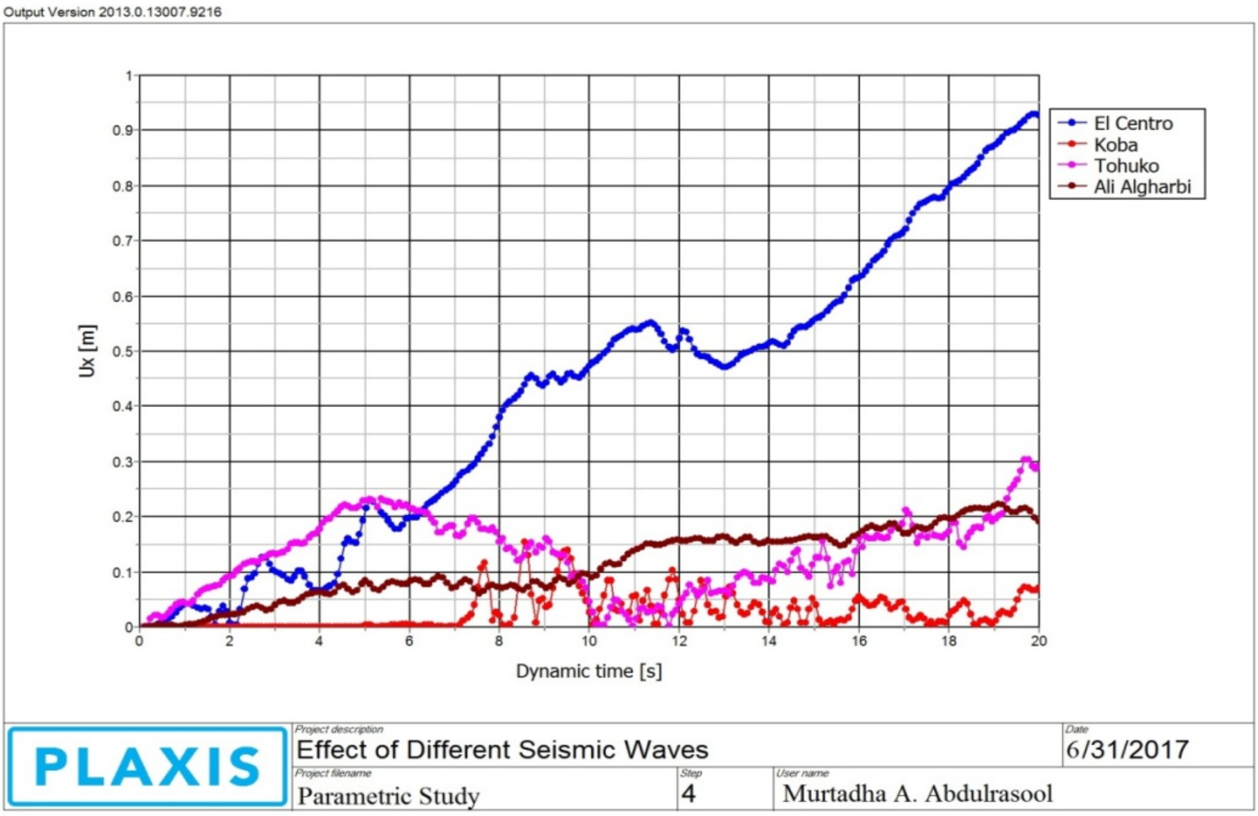


Fig. 10 Dynamic time versus lateral displacement in soil for different seismic waves

Fig. 11 shows the maximum vertical settlement for different earthquakes excitation which indicated that the maximum value is in site WS_6 affected by El-Centro earthquake and value of vertical settlement was 40 mm. It has been observed that the maximum vertical settlement for El-Centro earthquake is about 81% more than that Kobe earthquake for the same sites. This may be due to the high nonlinearity of soils as estimation of seismic response of foundation during a strong earthquake is a complex task because soil behaves in a highly nonlinear manner when subjected to large cyclic strains [2]. Also, Yadav and Jawaid [6] proved an important reduction of the bearing capacity of foundation with increasing of the maximum earthquake acceleration, which highlights the need to obtain a measure of the reliability associated with both calculation methods and safety factors commonly used for seismic design.

For the bending moment that occurred at the raft foundation with the different earthquakes excitations, the maximum value calculated at site S4 which is recognized by a soft clay soil and different in seismic waves velocities effecting on value of bending moment. Fig. 12 shows the maximum bending moment at raft foundation for different earthquakes for sites N4, EN6, WN4, M7, W2, E2, WS6, ES4 and S4. It has been observed that the maximum bending moment for EL-Centro earthquake is about 86% more than Kobe earthquake for all sites model.

Fig. 11 Effect of different seismic waves on vertical settlement of raft foundation

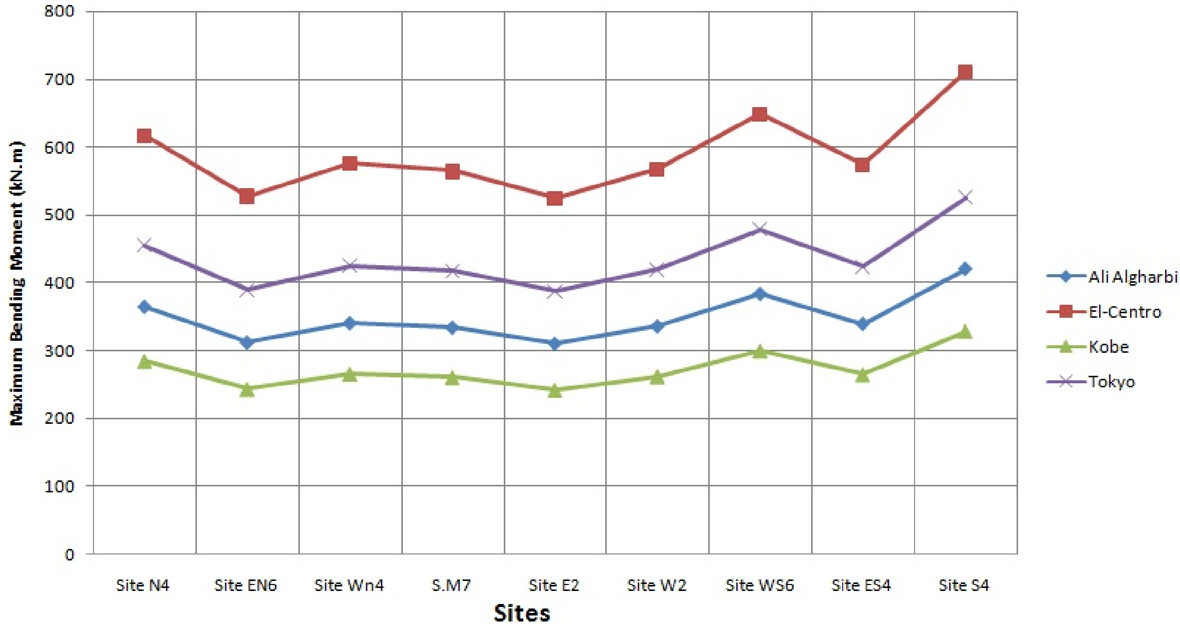


Fig. 12 Maximum bending moment at raft foundation in different seismic waves and different sites

C. Effect of Different Damping Ratio

Assuming constant viscous damping ratio for reinforced concrete buildings, typically 2% or 5% is common practice in structural design of such structures, regardless to the level of drifts. The study of seismic response with damping ratio for a different nominal damping range 5% is necessary for the analysis, design criteria and estimated the implementation of the structure based on the seismic engineering. These response spectra are also fundamental for designing and determining seismic isolation structures and energy dispersal systems and for the displacement procedures on the basis procedure, the structure of multi-degree of freedom is replaced by an equivalent single degree of freedom structure (alternative structure) characterized by hardness in order to withstand the maximum displacement response and equivalent viscosity damping, and the equivalent viscous damping of the alternative structure is much higher than 5% of the critical damping [9]. And to study the effect of damping ratio on the behavior of raft foundation for different locations, damping ratios of (0,2.5,5,7.5%) are used in the model study by PLAXIS 3D. Fig. 13 shows the effect of damping ratio on the lateral displacement of soil under raft foundation, the results show slightly change in value of lateral displacement of soil but at zero damping ratio large change in the curvature diagram of lateral displacement of soil has appeared, and it has been observed that the value of maximum lateral displacement at zero damping ratio is about 14% more than the value for damping ratio 7.5% and for all sites model. It can be indicated that the damping ratio may decrease the seismic wave and therefore may decrease the lateral displacement on soil under raft foundation.

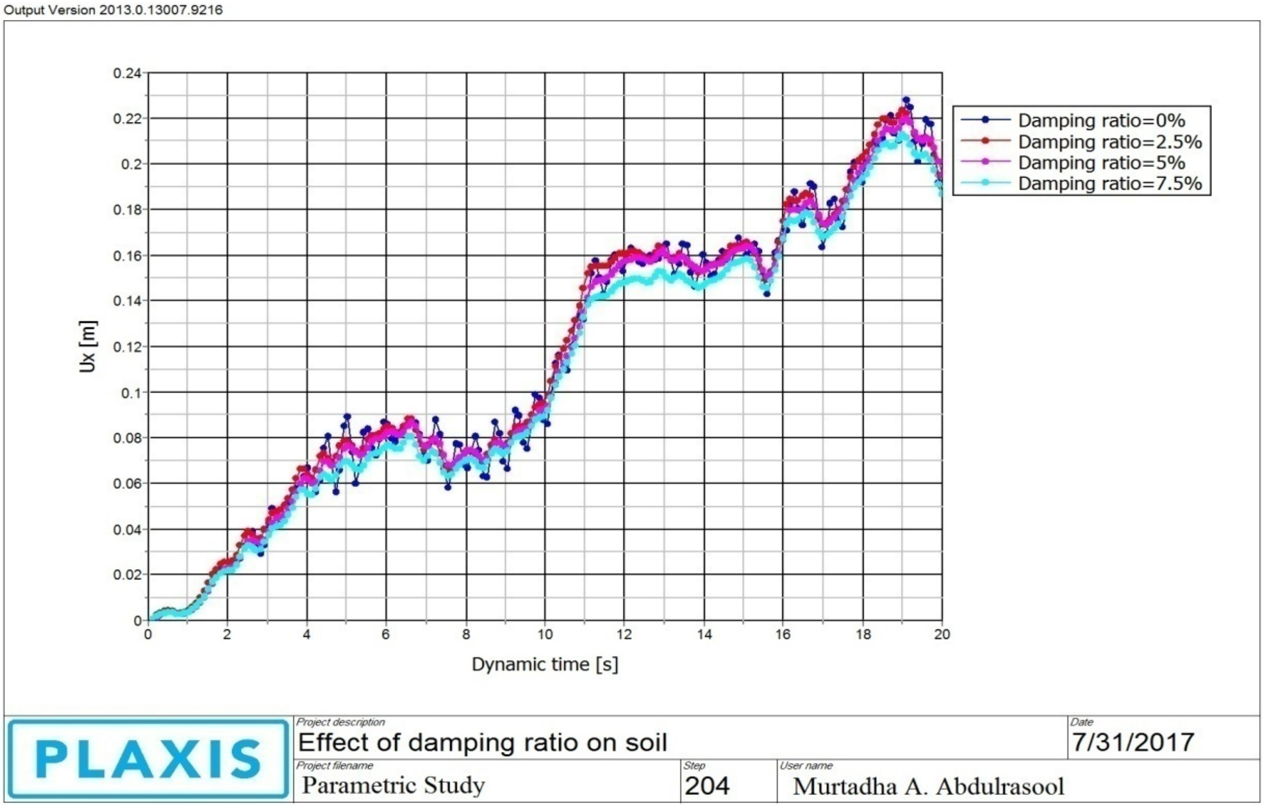


Fig. 13 Dynamic time versus lateral displacement in soil for different damping ratio

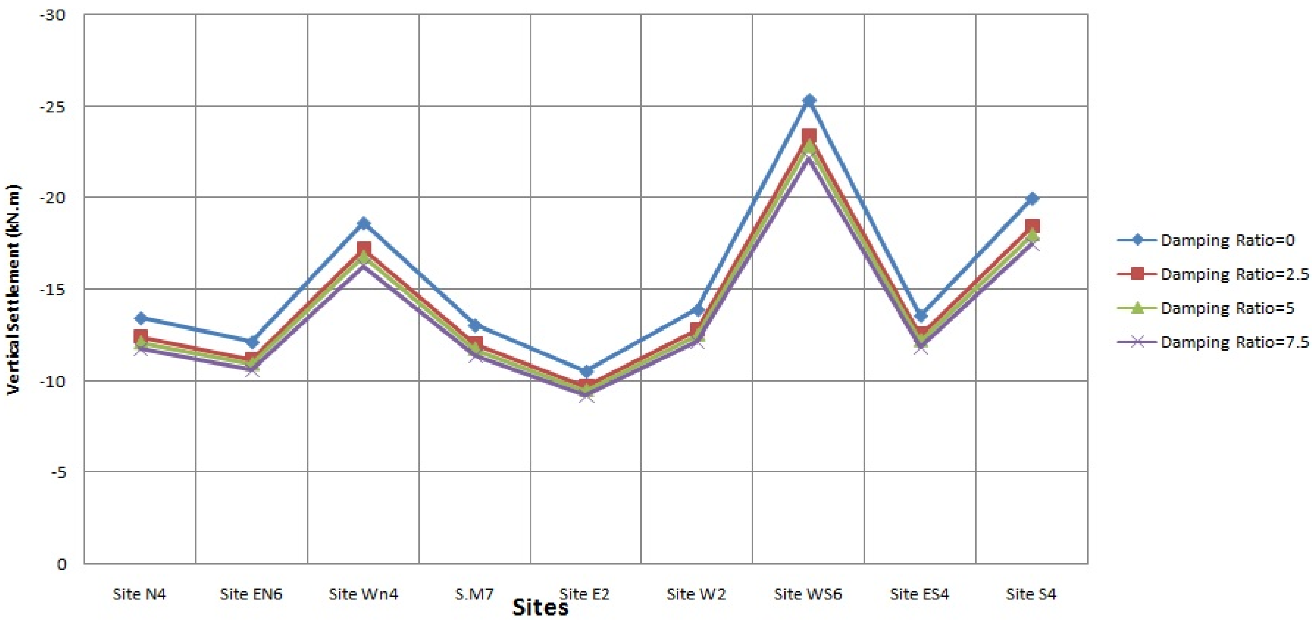


Fig. 14 Effect of different damping ratio in vertical settlement of raft foundation for different sites

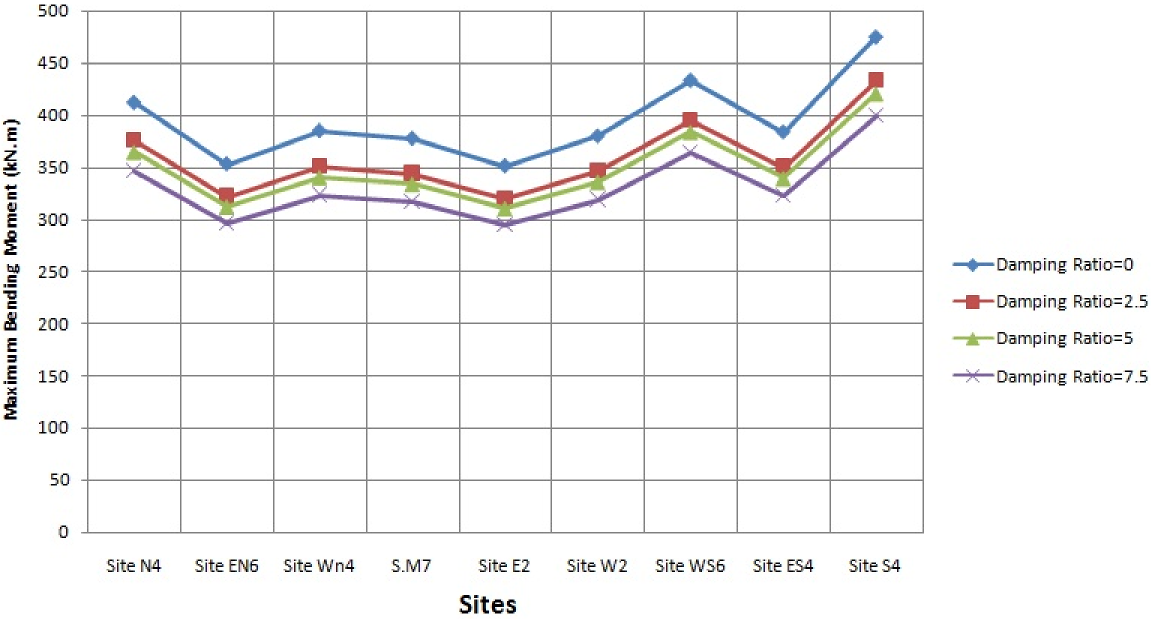


Fig. 15 Maximum bending moment at raft foundation in different damping ratio and different sites

The maximum vertical settlement that occurred at the raft foundation for different sites location in Iraq using different damping ratio, shows slightly changed in values as shown in Fig. 14, and it has been observed that the maximum vertical settlement for damping ratio, 0% is about 20% more than that for damping ratio 7.5% for all sites model.

For the bending moment that occurred at the raft foundation with the different damping ratios, the maximum value occurred at zero damping ratio which can be indicated that the damping ratio decrease the forces of earthquakes excitation as shown in Fig. 15, and it has been observed that the maximum bending moment for damping ratio, 0% is about18% higher than that for damping ratio 7.5% for all sites model.

VII. Conclusions

a) The maximum lateral displacement for the raft foundation is 5.8 mm at depth 2 m for S4 site in the South Zone. The maximum vertical settlement in raft foundation was shown in Western South at site WS5 and the value is 27.2154 mm.

b) It can be indicated that the vertical settlement of foundation increased when thickness was decreased under the earthquake action for the same point loads values, the displacement caused by earthquake can be decreased by about 72% with increasing the thickness one and a half times. The maximum bending moment is also increased with increasing the raft thickness. It has been observed that the maximum bending moment for 0.5 m thickness of raft foundation is about 82% less than that for 1.5 m thickness in all sites model.

c) The displacement depends on the local magnitude of the seismic wave and the peak ground acceleration which appears to be the highest at the El-Centro earthquake. The maximum value of lateral displacement is under El-Centro earthquake of magnitude (6.9 ML) and the minimum value under Kobe earthquake of magnitude (4.1ML) which is 40% less in magnitude. It has been observed that the maximum lateral displacement for El-Centro earthquake is about 92% more than that Kobe earthquake for the same sites. In addition, for the maximum vertical displacement, it has been observed that for El-Centro earthquake is about 81% more than that for Kobe earthquake for the same sites.

d) The bending moment that occurred at the raft foundation with the different earthquakes excitations showed the maximum value at site S_4 is 710.76 kN.m where the soil is soft clay and the difference in seismic wave's effect on the value of bending moment. It has been observed that the maximum bending moment for EL-Centro earthquake is about 86 % more than Kobe earthquake for all sites model.

e) The damping ratio may decrease the seismic wave and therefore decreased the lateral displacement on soil under raft foundation, the maximum lateral displacement for damping ratio, 0% is about 14% more than that for damping ratio 7.5% for all sites model and the maximum vertical settlement of raft foundation for damping ratio 0% is about 20% more than that for damping ratio 7.5% for all sites model. The maximum bending moment for damping ratio, 0% is about 18% higher than that for damping ratio 7.5% for all sites model.

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