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Effect of Foundation Flexibility on the Seismic Performance of a High-rise Structure under Far-field and Near-field Earthquakes

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ABSTRACT

In this study, the seismic performance of a 20-storey steel structure with a mat foundation located on layered soil is investigated under an array of strong ground excitations, which includes 6 far-fault and 6 near-fault earthquakes. Eight different modes for soil layering have been considered in the numerical simulation. FLAC 2D nonlinear platform has been used to model the near-realistic behavior. To this end, hundred lines of codes and subroutines have been developed in this platform to perform the analysis. The results of the analyzes include the absolute displacement of the floors, the ratio of the relative displacement of the floors, the shear force, the axial force, and the bending moment of the columns. It was concluded that for a 20-story structure on a mat foundation under both far-field and near-field earthquakes, the most reliable type of soil is the dense sandy soil and the most critical case is the soft clay soil. It was also observed that the near-field strong ground motions have imposed more critical structural responses compared to far-field records.

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1. INTRODUCTION

Due to the seismicity and the existence of active faults in many parts of the world, the study of the effect of foundation flexibility on the seismic behavior of buildings is of great importance, so extensive studies have been conducted in this field [1-4]. It has been observed that the performance levels of models with flexible foundations, especially in severe earthquakes, may change significantly compared to structures with rigid foundations. However, for moment-resisting frames on soft soils, flexible foundations have a significant effect on displacement and force responses. This indicates the need to pay more attention to the behavior of flexible foundations in modern design in order to achieve more economical and safer structures [5]. Choosing the right type of foundation can significantly affect the response of the structure and the foundation of the building [6]. Although seismic waves probably pass through tens of kilometers of rock and cross only less than 100 meters of soil layer to reach the earth's surface, the greatest impact, and change in the characteristics of earth movements occur within the soil layer. Some limited studies have been conducted on the effect of foundation flexibility and soil types on the seismic performance of structures [7, 8]. The results showed that all types of soil amplify bedrock movements in the soil-structure interface, but with different degrees that the amount of amplification is affected by many factors such as soil type and its characteristics, earthquake frequency content, and building characteristics [9]. Soil modulus has also a significant effect on the natural period of the system and the overall performance of structures [10]. Lateral displacement and internal forces of columns such as shear force, axial force, and moment in columns increase for all building frames when soil type changes from hard to medium and from medium to soft [11]. The dynamic response of the structure to earthquakes is significantly affected by the interaction of the structure and the foundation and the soil beneath the foundation.

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Soil-structure interaction is important for heavy structures, especially for high-rise buildings located on soft soils [12]. Many studies have evaluated the effects of soil-foundation-structure interaction on the seismic response of buildings with different types of foundations on different soils [13, 14]. Interaction affects the amplitude of the displacement of the foundation and depends on the frequency of seismic waves [15]. The results show that the fundamental natural period and base shear of a structure considering the interaction is greater than the non-interaction state, and with increasing the soil shear modulus and the number of stories, the fundamental natural period, the base shear, the maximum lateral displacement, drift ratio and moments in structure would increase [16-18]. Hence, upper stories displacements are more affected with soil-foundation-structure interaction (SFSI) than the lower stories [19]. Therefore, it is essential to consider the effects of SFSI in the seismic design of building frames, especially when located on soft soil [20].

According to the studies described above, various software such as ABAQUS, PLAXIS, SAP2000, ETABS, etc. has been used for modeling such the phenomenon. In this study, FLAC nonlinear platform was used for the simulation. A variety of behavioral models are defined in this program that allows researchers to model and analyze various problems under nonlinear analysis. One of the capabilities of this software is the ability to dynamically analyze geotechnical problems to model harmonic loads, earthquake loads, and explosions [21]. According to the subject of study and as this platform is more reliable especially in damping modeling, this software was used for numerical analysis. In this research, extensive investigations have been performed to study the seismic performance of a high-rise building with a mat foundation on different types of soil layers under various earthquake ground motions. Different engineering demand parameters (EDP) such as floor displacement, drift ratio, and internal forces of the columns have been investigated.

2. MODELING PROCEDURE

The nonlinear environment of FLAC software, which is a finite difference program, was used to model the near-realistic behavior. First, a soil layer was modeled according to the Mohr-Coulomb nonlinear constitutive model using this platform [22]. The Mohr-Coulomb model is one of the most common models that well introduces shear failure in soil and rock. This model has been selected due to its simplicity and reputation compared to other available complicated models used to represent shear failure in soils and rocks. Many of the current research works in the field of SSI are using this model to simulate the failure phenomena in soil materials. Hence, the simulated models would be quite reliable. The general form of the Mohr-Coulomb failure criterion is shown in Figure 1. The failure path from point A to point B is introduced using the Mohr-Coulomb yield function.

$$f^s = \sigma_1 - \sigma_3 N_\varphi + 2c\sqrt{N_\varphi} \tag{1}$$

The tension yield function also occurs in path B to C using the following function.

$$f^t = \sigma^t - \sigma_3 \tag{2}$$

In these relations φ is the angle of internal friction, c is the cohesion, σt is the tensile strength and N_φ is:

$$N_\varphi = \frac{1+sin\varphi}{1-sin\varphi} \tag{3}$$

According to Kuhlemeyer and Lysmer [23] to accurately represent the wave transmission through a model, the spatial element size, Δl, should be smaller than approximately one-tenth to one-eighth of the input wavelength associated with the highest frequency of the input wave.

$$\Delta l \leq \frac{\lambda}{10} \tag{4}$$

To have a computationally efficient model, mesh sensitivity analysis has been conducted to find the optimal mesh size based on the above formulation removing frequency values greater than 10 Hz.

After modeling the soil layers, the foundation and then the structure were modeled. Due to the fact that in this study, a high-rise structure is used and the superstructure loads are relatively large, and also different modes of soil layering are used, in some cases several types of soil are used and the subgrade is variable, and in some cases the subgrade is weak, so in order to minimize non-uniform settlements and deal with local complications and case weaknesses in the subgrade, mat foundation has been used for all cases. Different methods are common for the mat foundation analysis, the two main groups of which are rigid and nonrigid. In this

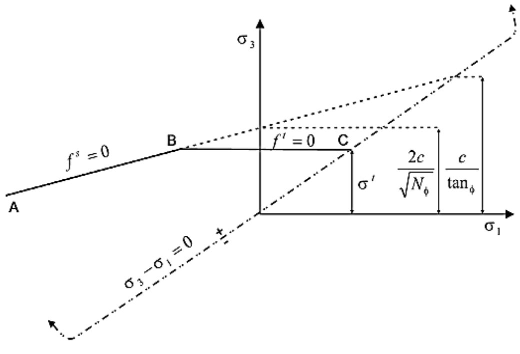


Figure 1. Mohar-Coulomb failure criterion [21]

study, the rigid solution is used for the mat foundation, which is known as the conventional method of static equilibrium. In this method, it is assumed that the foundation is much stiffer and harder than the subgrade [24]. After completing the modeling steps, earthquake acceleration records were applied to the lowest soil layer. All the mentioned steps including modeling, dynamic analysis, etc. have been done by developing the codes and sub-routines in FLAC 2D. As the investigated models are symmetrical both in plan and elevation, 2D models provide satisfactory results and are reliable. On the other hand, 2D models have fewer degrees of freedom (DOF) compared to 3D models and are more computationally efficient. It should be noted that in this study, nonlinear properties of the soils and steel materials have been used and the stress-strain curves of steel and concrete are shown in Figures 2 and 3, respectively.

2. 1. Modeling Approach Validation

To validate the numerical modeling approach used in the present study, a 4-storey building on a strip foundation on a soil layer was modeled and its seismic performance was investigated. FLAC 2D nonlinear environment was used to model the near-reality behavior. The results of modeling were compared with the simplified nonlinear model of Tahghighi and Rabiee's research results [5]. The modeling steps are as follows: first, the soil layers were modeled according to Mohr-Coulomb behavioral model

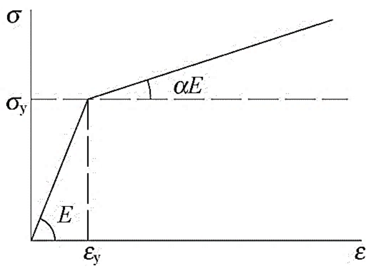


Figure 2. Bilinear stress-strain curve used for steel material [5]

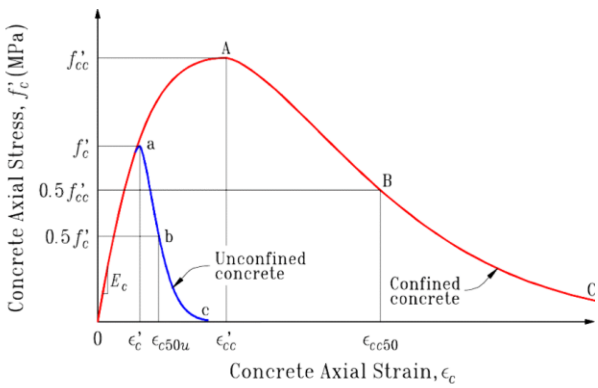


Figure 3. Curvilinear stress-strain relationship for confined concrete material [25]

using FLAC software, and then the strip foundation and the main structure were modeled. Finally, the obtained model is shown in Figure 4. After completing the modeling steps, the selected earthquakes were applied to the lowest layer of soil, which is the bedrock. All geotechnical, structural, and earthquake characteristics used are given in Tables 1-4.

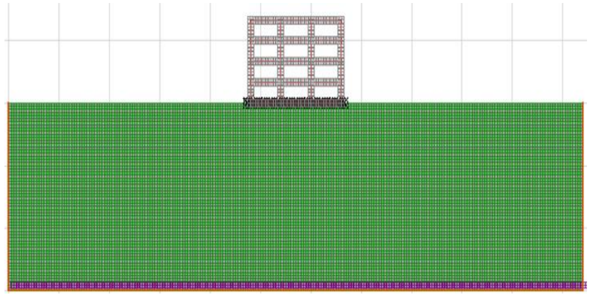


Figure 4. Building, soil layer and foundation modeled in FLAC software

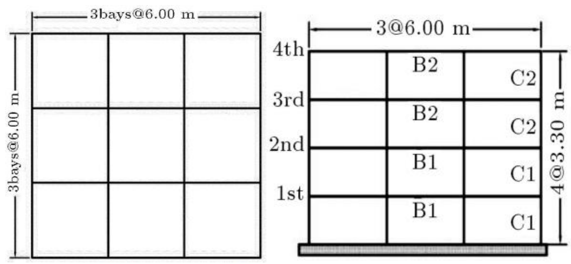


Figure 5. Plan and Elevation of the studied structure for verification [5]

TABLE 1. Sections of beams and columns [5]

Section tag	Web		Flange	
	Depth (cm)	Thickness (cm)	Width (cm)	Thickness (cm)
C1	31.96	2.11	39.88	3.33
C2	32.10	1.64	37.34	2.62
B1	27.84	1.09	30.48	1.70
B2	27.65	0.99	30.48	1.54

TABLE 2. Details of soil parameters used [5]

Φ (degree)	C (kg/cm^2)	υ	G(kgf/cm^2)	Vs(m/s)
30	0.15	0.35	6707	560

TABLE 3. Specifications of the foundation used [5]

Footing type	B (m)	L (m)	H (m)	q_{all} (kgf/cm^2)	K_s (kgf/cm^3)
strip	1	19	0.65	2	2.40

TABLE 4. Specifications of used earthquakes for verification [5]

No.	Earthquake	Year	Station	Mw	D (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	Northridge, USA	1994	Old Ridge Route	6.7	22.6	0.57	52.1	4.2
2	Cape Mendocino, USA	1992	Rio Dell Overpass	7.1	18.5	0.55	42.1	18.6
3	Chi-Chi, Taiwan	1999	TCU045	7.6	24.0	0.51	39.0	14.3
4	Loma Prieta, USA	1989	Gilroy Gavilan Coll.	6.9	12.0	0.36	28.6	6.3
5	San Fernando, USA	1971	Lake Hughes	6.6	20.3	0.37	17.0	1.6
6	Victoria, Mexico	1980	Cerro Prieto	6.1	17.0	0.62	31.6	13.2
7	Whittier Narrows, USA	1987	LA-116th St School	6.0	22.5	0.39	21.0	1.8

After completing the dynamic analysis, the time history diagrams of the displacement of the floors in FLAC software were examined and were compared with the results of Tahghighi and Rabiee's research for DBE and MCE hazard levels in Figure 6. As can be seen, this comparison indicates that the results are almost identical to each other and the modeling approach in the current study is verified. The model proposed in the current study is more comprehensive compared to Tahghighi and Rabiee's research [5], as the soil-structure-interaction (SSI) have been implemented with more details and near the realistic behavior. The purpose has not been to develop a model for practical engineering application as it has been a scientific investigation considering as much complexity and uncertainties in models as possible.

3. STRUCTURAL AND GEOTECHNICAL SPECIFICATIONS OF THE MODEL

In this study, a 20-storey steel moment-resisting frame building located on 8 soil layering modes and a mat foundation has been investigated. This building model has a floor plan of 30.48× 36.58 m^2 and its total height is 80.77 m. The bays are 6.1 m, as shown in Figure 7. Floors are made of composite slabs and the building's lateral load-resisting system consists of steel perimeter moment-

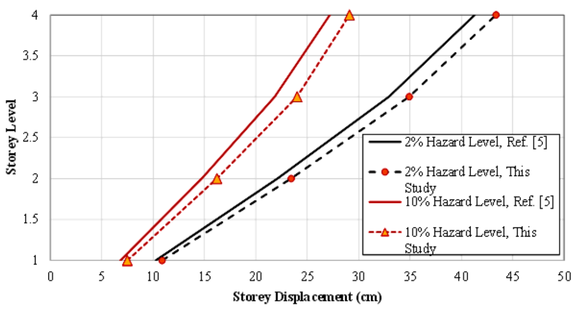


Figure 6. Model validation at two hazard levels [5]

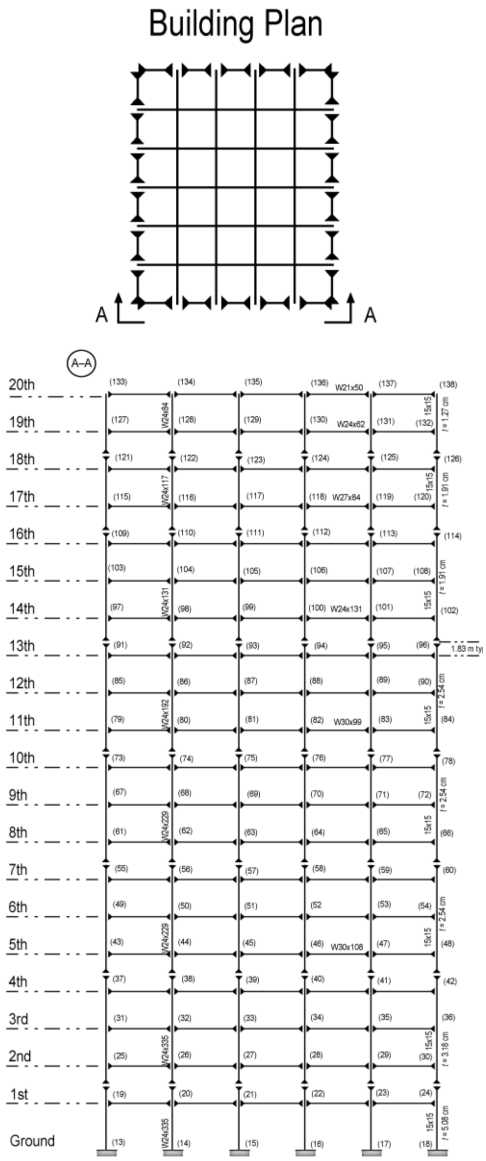


Figure 7. Specifications of the investigated 20-storey structure [22]

resisting frames (MRFs). The type of steel selected for the beams and columns of the structure is of St-37 type. The middle columns of the MRF are wide flange but the corner columns are BOX type. The typical heights from floor to floor are 3.96 m and only the height of the first floor is 5.49 m. The building has been selected from pre-designed SAC project models [22]. The amount of live load is considered as 200 kg/m^2, while the dead load is 500 kg/m^2, and the live load reduction coefficient is considered as 20%. The characteristics of the investigated structure and it's plan are shown in Figure 1.

The complete characteristics of the soils used in this study are presented in Tables 5 and 6. The soils are layered and named in 8 different categories.

TABLE 5. Specifications of soil layers used in this study [3,4,24]

Soil type	G (Pa)	K (Pa)	E (Pa)	ν	C (Pa)	Φ (deg)	γ (kg/m^3)
Soft clay	8.40×10^6	5.70×10^7	2.4×10^7	0.43	5× 10^4	20	1575
Medium stiff clay	15.84×10^6	9.37×10^7	4.5×10^7	0.42	9× 10^4	24	1595
Stiff clay	19.23×10^6	4.16×10^7	5.0×10^7	0.30	12× 10^4	26	1500
Loose sand	23.08×10^6	5.00×10^7	6.0×10^7	0.30	0	28	1500
Medium density sand	35.18×10^6	10.55×10^7	9.5×10^7	0.35	0	33	1900
Dense sand	57.90×10^6	24.39××10^7	16.1×10^7	0.39	0	38	2000

TABLE 6. Soil categories used in this study

Type / Layer Number	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5	Soil 6	Soil 7	Soil 8
1st Layer	Loose sand	Medium density sand	Dense sand	Loose sand	Soft clay	Medium stiff clay	stiff clay	Soft clay
2nd Layer	Loose sand	Medium density sand	Dense sand	Medium density sand	Soft clay	Medium stiff clay	stiff clay	Medium stiff clay
3rd Layer	Loose sand	Medium density sand	Dense sand	Dense sand	Soft clay	Medium stiff clay	stiff clay	stiff clay

The concrete used in the design of the foundation has a modulus of elasticity E_c = 2.2×1010 (Pa) compressive strength f_c = 2.1×107 (Pa), Poisson ratio υ = 0.2. The foundation is designed as a Mat foundation with the moment of inertia (I) of 1.302 m^4 and the cross-section area (A) of 2.5 m^2 for a unit width. The schematic presentation of the developed model in FALC is depicted in Figure 8.

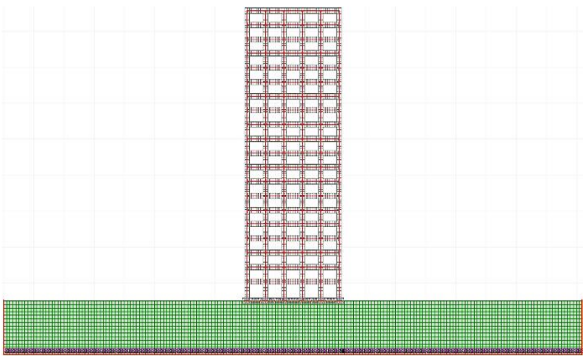


Figure 8. Building, soil layer and foundation modeled in FLAC nonlinear platform

4. STRONG GROUND MOTIONS USED

Twelve earthquake records were applied to the models, 6 of which are far-fault earthquakes and the other 6 are near-fault earthquakes, and all are taken from the FAMA P695 database [26]. To make sure that the residual velocity or displacement will not affect the final outcome, baseline filtering has been applied to them [21]. To match the design response spectra, ASCE 7 procedure has been used for the scaling procedure. A 5% Rayleigh damping is considered as the inherent damping of the investigated structure. To get the most accurate results, the excitations have been applied to the bottom of the lowest layer, representing the bedrock. Earthquake records' characteristics are given in Tables 7 and 8.

5. RESULTS AND DISCUSSION

In this part, the seismic performance of a SAC project high-rise steel structure on layered soils is investigated and the results are discussed. Nonlinear time history analyzes were performed using FLAC 2D software and the results of various EDPs were obtained, which are compared and discussed below.

5. 1. Time History Analysis Nonlinear dynamic time history analyzes have been performed using strong ground motion records proposed in Tables 7 and 8. A total of 96 time-history analyzes were performed to study the seismic performance of this structure, as shown in Figures 9-17. Floor displacement, drift ratio, maximum axial force, shear, and moment in columns have been selected as the most important response parameters to estimate the seismic behavior of the structure in this study.

5. 1. 1. Absolute Displacement The maximum absolute displacements of all structural floors on eight soil types were obtained under all earthquake records. Finally, the average displacement of each floor in all soil types was calculated. Then, the diagrams of the average floor displacement for the investigated structure were obtained, which are shown in Figures 9 and 10. The horizontal axis shows the average displacement of the floors and the vertical axis shows the level of floors. As shown in Figures 9 and 10, the displacement of floors increases with increasing floor height, but the rate of increase in displacement in the lower floors is more significant than in the upper floors. Figure 9 shows the average displacement for all soil types under far-fault and near-fault earthquakes. As can be seen, the displacement of floors in the case of clay soils is more than the sandy soils, and the highest displacement is related to type 5 soil (soft clay), while the lowest displacement is related to type 3 soil (dense sand). As shown in Figure 9(a), the displacement range of the floors for the 20-story structure under far-field earthquakes is 0.025-0.371 m, whilst in Figure 9(b) the displacement range for near-field earthquakes is 0.045-0.706 m, which is much greater than that of the far-field case.

Figure 10 shows the average floor displacement for all earthquakes in two categories. In Figure 10, the average floor displacement range for all far-fault earthquakes has been 0.023-0.482 m; while the range for the near-field earthquakes has been 0.025-0.944m. According to the mentioned ranges, the average floor displacement under near-fault records is significantly higher than the far-fault ones. Imperial Valley – 06 El Centro and San Fernando earthquakes in the far-fault category, and Imperial Valley - 06 El Centro and Superstition Hills - 02 earthquakes in the near-fault category have caused the highest storey displacements.

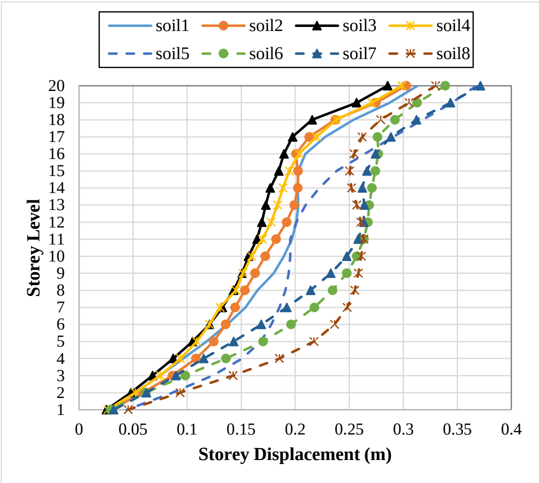
Figure 11 shows the average displacement of floors for all types of soils under different earthquake categories. In Figure 11, the range of floor displacement for all soil types in all far-fault earthquakes has been 0.032-0.325 m, while the range for the near-fault earthquakes has been 0.052-0.563 m.

TABLE 7. Characteristics of selected far-field earthquakes [25]

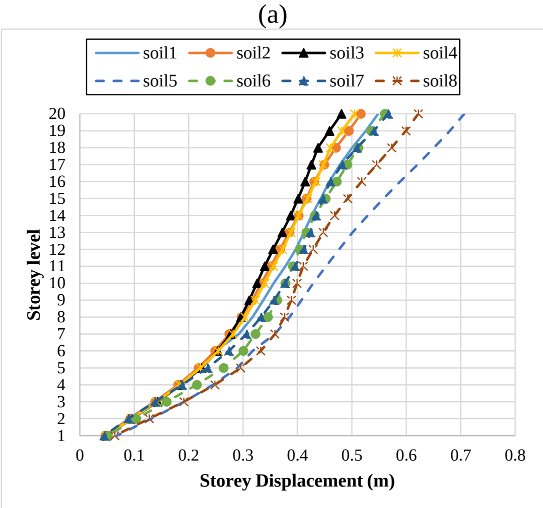
Record Number	Earthquake Name	Station Name	Magnitude (MW)	PGAmax (g)	PGVmax (cm/s)
1	San Fernando	LA-Hollywood Store FF	6.6	0.21	**19**
2	Imperial Valley-06	Delta	6.5	0.35	**33**
3	Imperial Valley - 06	El Centro Arrey #11	6.5	0.38	**42**
4	Northridge - 01	Beverly Hills-Mulhol	6.7	0.52	**63**
5	Loma Prieta	Capitola	6.9	0.53	**35**
7	Landers	Coolwater	7.3	0.42	**42**

TABLE 8. Characteristics of selected near-field earthquakes [25]

Record Number	Earthquake Name	Station Name	Magnitude (MW)	PGAmax (g)	PGVmax (cm/s)
26	Landers	Lucerne	7.3	0.79	**140.3**
24	Cape Mendocino	Petrolia	7.0	0.63	**82.1**
32	Northridge- 01	Rinaldi Receiving Sta	6.7	0.87	**167.3**
8	Imperial Valley - 06	El Centro Arrey 06	6.5	0.44	**111.9**
14	Superstition Hills - 02	Parachute Test Site	6.5	0.42	**106.8**
20	Loma Prieta	Saratoga – Alloha Ave	6.9	0.38	**55.6**

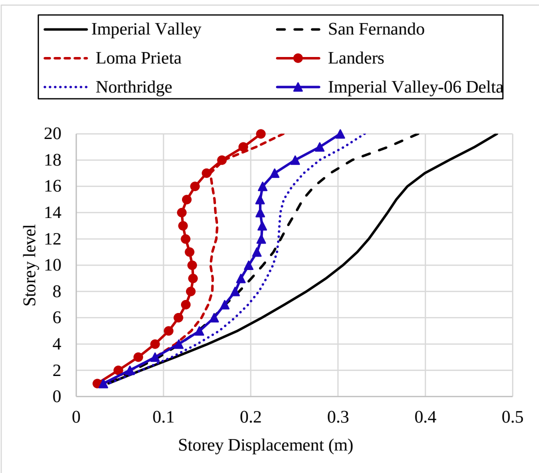


(a)

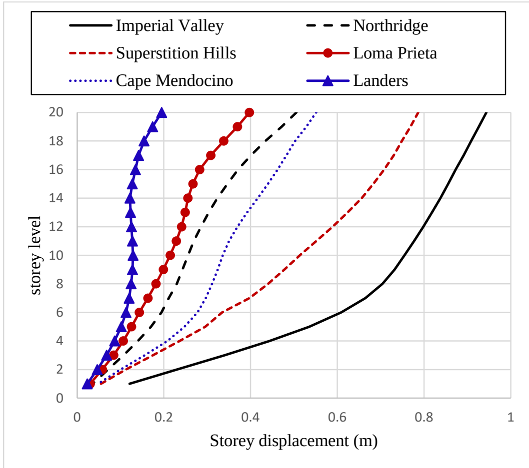


(b)

Figure 9. Average displacement of the building under (a) far-fault, and (b) near-fault



(a)



(b)

Figure 10. Average floor displacement for earthquakes: (a) far-fault, and (b) near-fault

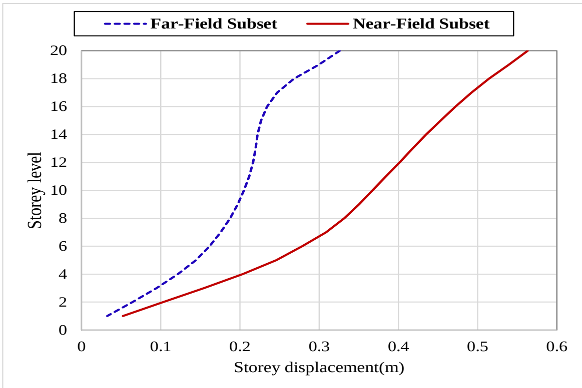


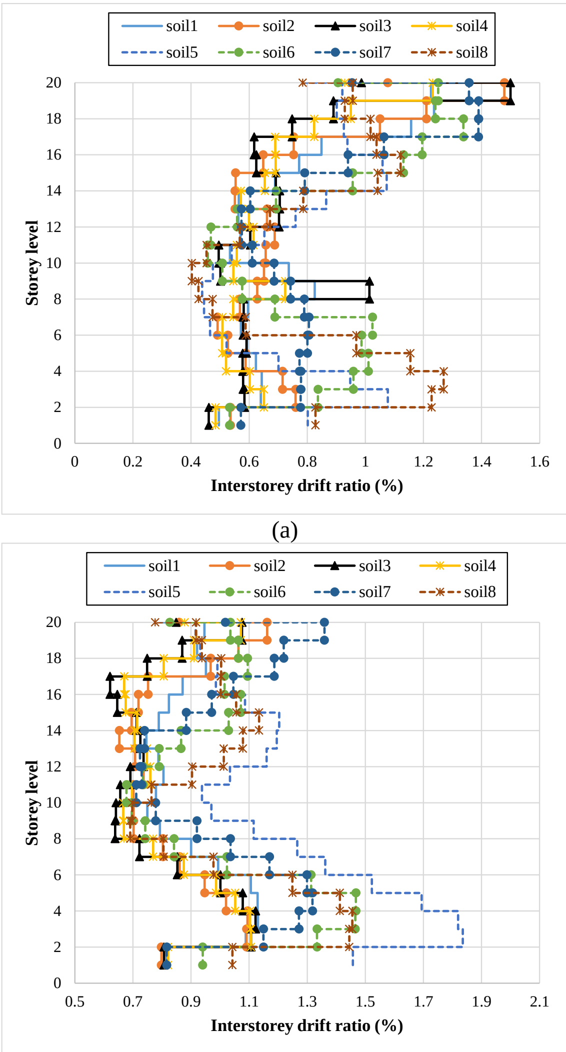
Figure 11. Average floor displacement in all earthquakes and all soils

5. 1. 2. Drift Ratio Drift Ratio is the most commonly used EDP to determine damage level in a structure. Figure 12 shows the average drift ratio of structural floors for all types of soils under near-fault and far-fault earthquakes. As shown in this figure, the drift ratios are higher in the first and last floors of the structure, and in these areas, the drift ratio has an increasing trend. The maximum drift ratio of floors for all soils under far-fault earthquakes according to Figure 12(a) is related to dense sand soil and medium-density sand, which are 1.5% and 1.48%, respectively. According to Figure 12(b), the maximum drift ratio for all soils under near-fault earthquakes is related to soft clay with a value of 1.83%. Therefore, the maximum average ratio of structural floors of near-fault earthquakes is higher than the earthquakes far from faults.

Figure 13 shows the graphs of the average floor drift ratio for all earthquakes in areas far from the fault and near the fault. In Figure 13(a), the San Fernando earthquake has caused the highest floor drift ratio of 1.6%. In Figure 13(b), the Imperial Valley-06 El Centro Earthquake has induced a drift ratio of 2.8, which has been the highest drift ratio.

Figure 14 shows the average drift ratio of structural floors. As can be seen in this figure, the maximum average drift ratio has been 1.24% under earthquakes far from faults and the highest drift ratio has been about 1.31% in near-fault earthquakes. According to the diagram, it can be seen that the drift ratio is higher in the first and last floors.

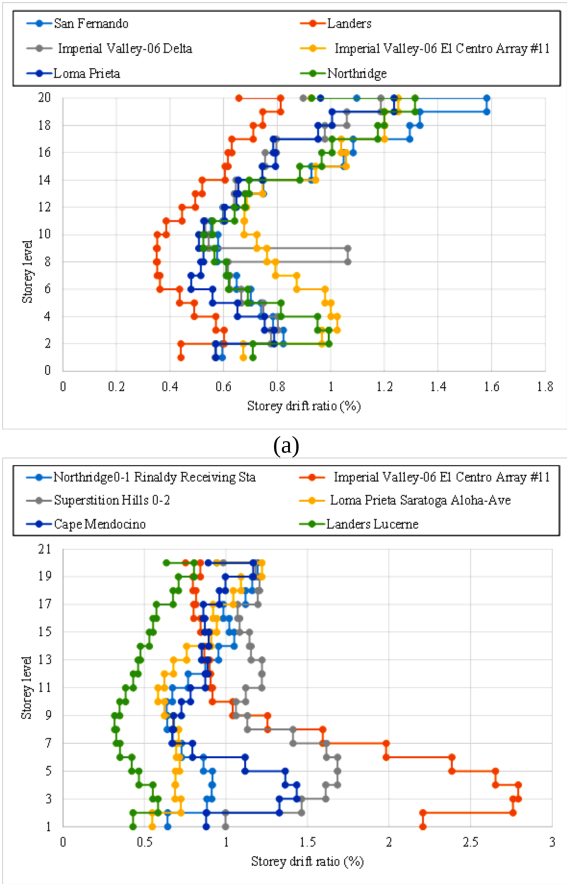
5. 1. 3. Internal Forces As shown in the diagrams above, the highest displacement and drift ratio is related to soft clay in the Imperial Valley-06 El Centro earthquake in the near-fault areas, which was determined



(a)

(b)

Figure 12. Average ratio of relative displacement of structural floors: (a) far-fault, and (b) near-fault



(a)

(b)

Figure 13. The average ratio of relative displacement of structural floors (a) far-fault, and (b) near-fault

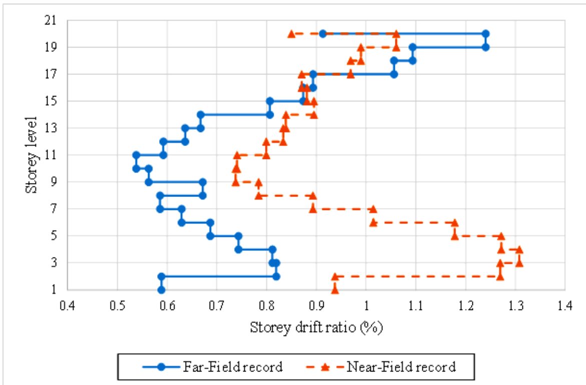


Figure 14. Average ratio of relative displacement of structural floors in all earthquakes and all soils

as the most critical case. Thus, soft and stiff clay were selected under the Imperial Valley-06 El Centro earthquake in the area near the fault to make a comparison between the results of the internal forces of the columns in terms of soil stiffness. The internal forces of the columns include the shear force, bending moment, and axial force of the middle and side columns. Figure 15 shows the shear force of the middle and lateral columns of the structure vs. the structural floors for stiff and soft clay soils under Imperial Valley-06 El Centro earthquake. As can be seen, with increasing the number of floors and the height of the structure, the values of shear forces decrease, so the diagrams have a downward trend. According to the diagram, the shear force of the middle columns is more than the shear force of the side columns. Also, the amount of shear forces in soft clay is more than stiff clay.

Figure 16 shows the bending moment values of the middle and lateral columns of the structure vs. the structural floors for soft and stiff clay soils in Imperial Valley-06 El Centro earthquake. As can be seen in the figure, the bending moment values decrease with the increasing number of floors and have a decreasing trend. The amount of bending moment for the middle columns is more than the side columns. Also, the shear forces for soft clay are more than for stiff clay.

Figure 17 shows the axial force of the middle and lateral columns of the structure versus the number of structural floors for soft and stiff clay soils in Imperial Valley-06 El Centro earthquake. According to the figure below, it can be seen that the axial force in the side columns is more than the middle columns and the values for soft clay are more than those for stiff clay, while in the middle columns the axial force values for these columns on soft clay are less than the stiff clay soil. Also, according to this diagram, it can be seen that the axial force of the columns decreases with the increasing number of floors and has a downward trend.

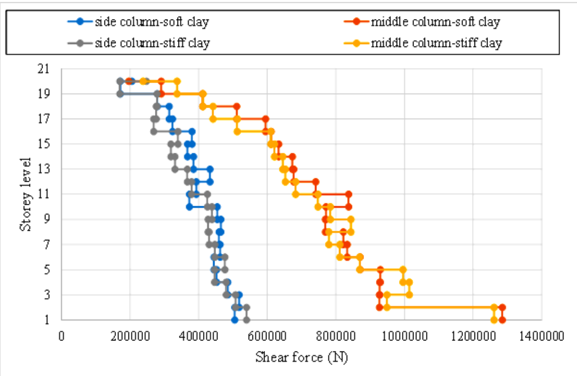


Figure 15. Shear force of side and middle columns of the structure in the Imperial Valley-06 El Centro earthquake in the area near the fault for soft clay and stiff clay

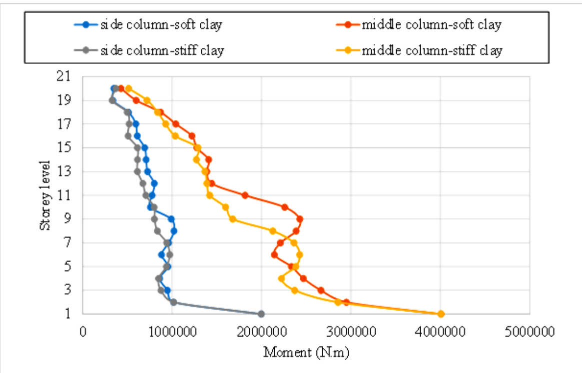


Figure 16. Bending moment of side and middle columns of the structure in the Imperial Valley-06 El Centro earthquake in the area near the fault for soft clay and stiff clay

5. 1.6. Maximum Principal Stress The following relation is known as Mohr-Coulomb relation and the criterion of Mohr-Coulomb rupture is based on literature [27]. The circle of Mohr and rupture envelope is shown in Figure 18.

$$\tau_f = c + \sigma_f \tan\varphi \tag{5}$$

In the above formulation, σ_f depends on the load and is a variable of shear strength. The value of σ_1 is increased by vertical loading until the Mohr circle touches the rupture line and the soil element is ruptured. In this case, σ_1, for which the Mohr circle is tangent to the rupture line, is the minimum principal maximum stress that

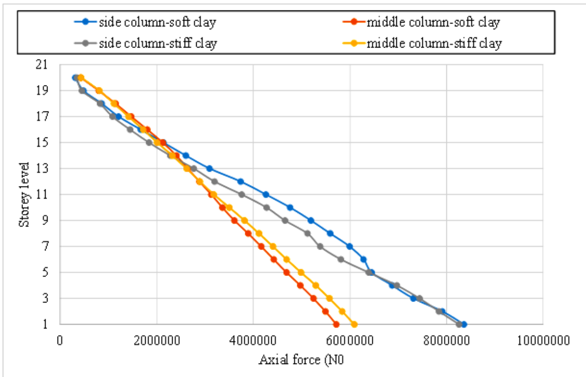


Figure 17. Axial force of side and middle columns of the structure in the Imperial Valley-06 El Centro earthquake in the area near the fault for soft clay and stiff clay

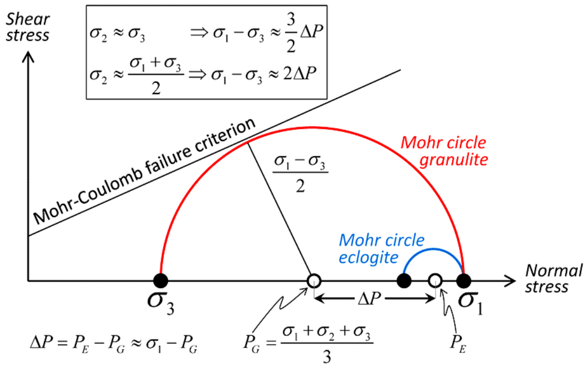


Figure 18. Mohr circle and rupture envelope [28]

causes a rupture in the θ direction in the soil element. The value of the rupture plane angle with the principal stress plane is given in Equation (6) [27].

$$\theta = 45 + \frac{\varphi}{2} \tag{6}$$

Equation (7) shows the relationship between the principal stresses at the moment of rupture, which is called the rupture relationship of the principal stresses [27]. Due to the importance of the principal maximum stress value of the σ_1 stress contour in the soil layers for more critical soils and earthquakes, it is shown in the following figures. Figure 19 shows the maximum principal stress in soft clay layers. Figure 20 shows the maximum principal stress for stiff clay layers. Figures 19 and 20 are related to the Imperial earthquake in the area near the fault.

$$\sigma_1 = \sigma_3 \times tan^2\left(45 + \frac{\varphi}{2}\right) + 2c \times \tan\,(45 + \frac{\varphi}{2}) \tag{7}$$

Figure 21 shows the maximum principal stress of the soft clay layer in the Imperial Valley-06 El Centro earthquake far from the fault. For the sake of brevity, only these figures are presented for the case of stress conditions in the soil types, while the rest has shown a similar trend.

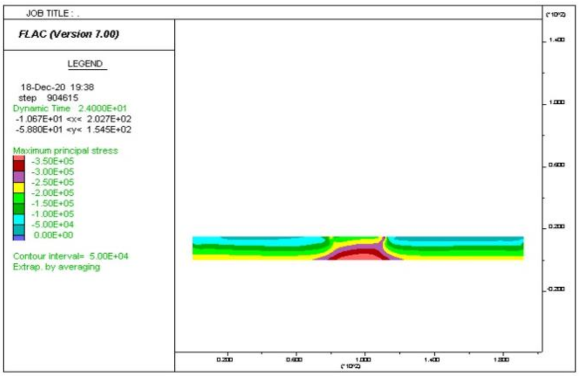


Figure 19. maximum principal stress in soft clay layers in Imperial Valley-06 El Centro earthquake

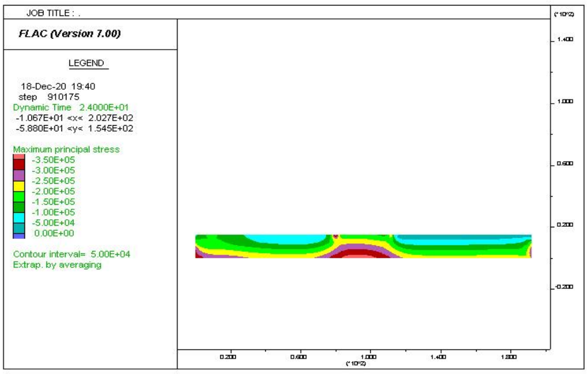


Figure 20. maximum principal stress in stiff clay layers in Imperial Valley-06 El Centro earthquake

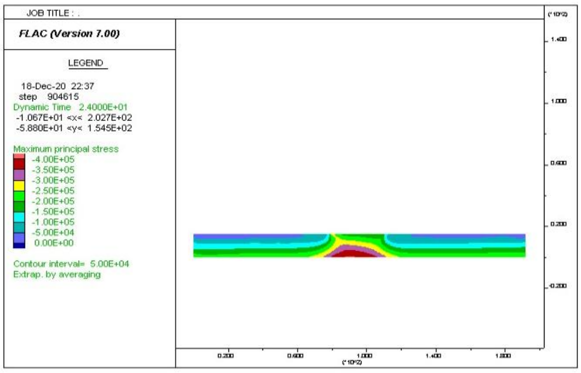


Figure 21. maximum principal stress in soft clay layers in Imperial Valley-06 El Centro earthquake

6. CONCLUSION

In this study, the seismic performance of a 20-story steel structure with a mat foundation on layered soils has been investigated. Nonlinear dynamics time-history analyzes were performed using strong ground motion records in FLAC platform. The results of the analysis include absolute floor displacement, floor drift ratio, the shear force, axial force, and bending moment of columns, which are described below:

The displacement of layers in clay soils is more than sandy soils so that the highest displacement is related to soft clay and also the least displacement is related to dense sand, so the most suitable soil for a 20-storey structure on a mat foundation under far- and near-fault earthquakes is dense sand and the most critical soil type would be the soft clay.

The results indicated that the maximum average drift ratio has been 1.24% under earthquakes far from faults and the highest drift ratio has been about 1.31% in near-fault earthquakes. It was also observed that the drift ratio is higher in the first and last floors.

The values of shear forces and bending moment in the middle columns are more than the side columns of the structure and the amount of shear forces and bending moment in soft clay is more than stiff clay, so the more flexible the soil, the higher the shear force and bending moment of columns. Internal forces decrease with increasing number of structural floors and have a downward trend.

7. RECOMMENDATIONS

The above results can be useful to help design and practicing engineers to consider the effects of soil and earthquake type on the seismic design of buildings. However, this study still needs to be extended for other types of structures with more floors with other structural systems. Other structural behavioral indicators, behavior coefficient, ductility coefficient, and resistance reduction coefficient can be investigated in future studies. It is also suggested to use incremental and pushover dynamic analysis for future studies. In this study, the behavioral model of Mohr-Coulomb for soil has been used. It is suggested that other behavioral models be investigated as well. In this study, mat foundation is considered as rigid, which can be further investigated as semi-rigid or non-rigid in future studies.

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Persian Abstract

چکیده

در این پژوهش، عملکرد لرزه ای سک ساختمان ۲۰ طبقه فلزی با فونداسیون گسترده روی خاک لایه ای تحت گروهی از شتاب نگاشت های حرکت شدید زمین شامل ۶ رکورد حوزه دور و ۶ رکورد حوزه نزدیک مورد مطالعه قرار گرفته است. ۸ لایه بندی مختلف خاک برای شبیه سازی عددی در نظر گرفته شده است. نرم افزار غیرخطی FALC 2D به منظور مدلسازی نزدیک به واقعیت مد نظر قرار گرفته است. برای این منظور صدها خط کد نویسی جهت انجام تحلیل ها صورت گرفته است. نتایج مستخرج شامل جابجایی مطلق کف ها، جابجایی نسبی طبقات و تلاش های داخلی در ستونها بوده است. نتیجه گیری شد برای یک ساختمان ۲۰ طبقه برروی فونداسیون گسترده تحت زلزله های حوزه دور و نزدیک، خاک ماسه ای متراکم و خاک رسی نرم به ترتیب بیشترین و کمترین قابلیت اعتماد را برای سازه ایجاد می نمایند. همچنین مشاهده گردید اثرات زلزله های حوزه نزدیک به مراتب بحرانی تر از زلزله های حوزه دور بوده است.