IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 19, Issue 4 Ser. III (Jul. – Aug. 2022), PP 42-56
www.iosrjournals.org

Soil-Structure-Interactions Effect in The Dynamic Damage Analysis of Seismic response of Irregular High-Rise Tower

Mahmoud Fakih[1], Jaafar Hallal[2], Ahmad Saade[3], Hassan Hamouch[4], HalaDamerji[5],
[1]*(Civil Engineering, Lebanese University, Beirut, Lebanon)*
[2]*(Mechanical Engineering, Lebanese University, Beirut, Lebanon)*
[3]*(Civil Engineering, Clermont Auvergne University, Clermont Ferrand, France)*
[4]*(Civil Engineering, Saint Joseph University, Beirut, Lebanon)*
[5]*(3SR, Grenoble-Alpes University, CNRS, Grenoble INP, France)*

Abstract:
In the present paper, the effect of soil conditions on an irregular high-rise building seismic response has been studied in a comprehensive manner. Using a nonlinear time history analysis, the study was carried out using Etabs-2018 software. In order to examine this soil effect in the dynamic damage analysis, the irregular high-rise building was subjected to different seismic signals. Those signals were matched with response spectrum using the time domain method. The objective of this research is to study whether soil-structure interaction (SSI) affects the seismic performance and the vulnerability of reinforced concrete shear-walls building and consequently to assess if there in any modification on the seismic performance curves. The differences in spectral accelerations, storey displacements, storey drifts, storey shear and base shear of the building, which are obtained based on the seismic provisions of IBC code, have been studied and compared based on different seismic signals. The study compared the seismic response of the building under three different soil types. A comparative analysis was performed for the model that highlights various trends in the seismic response of the considered SSI and fixed base system. The paper concluded that the hard soil and medium soil are suitable in reducing damage for base isolation building.

***Keywords**: Seismic damage; Irregular high-rise building; Soil-Structure-Interaction; Seismic response analysis.*

Date of Submission: 12-08-2022 Date of Acceptance: 27-08-2022

I. Introduction

An essential field in earthquake engineering analysis is the study of soil condition [1]. The SSI (Soil-Structure-Interaction) effects may influence the seismic demand and also the seismic capacity of structures referring to several researches and earthquake observations. It is an interdisciplinary field of science which encompasses the soil dynamics, the structural mechanics and so forth [2]–[4]. Generally, during the imposition of the loads of an earthquake, the structure is considered fixed-base disregarding the flexibility of the soil under the structure. Nevertheless, the soil deformation changes the characteristics of the free field motion at ground level with normally a change of the structure reaction against earthquake [5]–[7]. As a general rule, SSI yields to a diminishment in the base shear and an escalation in the structure period, the system damping and the contribution of the rocking mode to the total response.

The first researches in the domain can be traced back to the early 1930s with a particular insistence on SSI as a phenomenon influencing the dynamic behavior of structures. Reissner proposed the theory of investigating of foundation vibrations as the point of departure for SSI studies [8]. There are numerous studies which have shown a correlation between structural damage and site soil condition [9]–[11]. The application of SSI is accomplished by considering the inertial and kinematic interaction schemes. That leads to an elongation of the natural period of the soil-structure system and an increase of system damping as a result of energy dissipation at the soil-foundation level in comparison to the fixed base case [12]. Wolf et al. have elaborated the principles and the effects of SSI [13], the model of interaction soil-foundation and the equations of motion. They also introduced the analysis methods and their relevant responses. Several other researchers have studied the seismic analysis of SSI for different types of structures [14], [15, p. 59]. Some of them have highlighted the effects of elastic dynamic SSI on elastic and inelastic structural response [16], [17]. However, other researches concerning the nonlinear soil-structure systems have demonstrated an additional translation and rotation effects which increase the displacement demands of the structure [18], [19]. Sáez et al. have investigated an inelastic dynamic SSI effects on the seismic behavior of buildings [20]. The authors demonstrated that the soil deformability and SSI may affect the response and fragility of non-linear structures, causing either beneficial or unfavourable effects that depend as well on the imposed input motion to the fixed base superstructure. Rajeev et al. have studied the SSI effects on the seismic response of non-ductile concrete frames where they highlighted the influence of the soil properties [21], the foundation geometry and ground motion input characteristics for both linear and nonlinear soil behavior. It was interpreted that the fragilities of the fixed base models may be affected by SSI and the uncertainty in ground motion. Pitilakis et al. concluded that the consideration of SSI and site effects may alter the expected seismic performance of the buildings leading to higher vulnerability values and should therefore not be neglected for assessment purposes [22].

Two mainly approaches are commonly used to consider SSI phenomenon, namely the direct approach and the multi-step or the substructure approach [23]–[25]. In the direct soil analysis, the foundation and the structure are modeled as a single model and analyzed in one single step as exhibited in Figure 1. The advantage of this method is the capability of modeling a non-linear behavior of soil and structural materials with the possibility of modeling complex geometries. Nevertheless, their disadvantages are presented by the bulky volume of inputs and outputs, its complexity and the time calculation consumption. However, the substructure approach treats each component separately and then combines them to get the results [13], [26], [27], the linear problem of SSI is splitted into series of simpler problems then the results are incorporated using the principle of superposition [28].

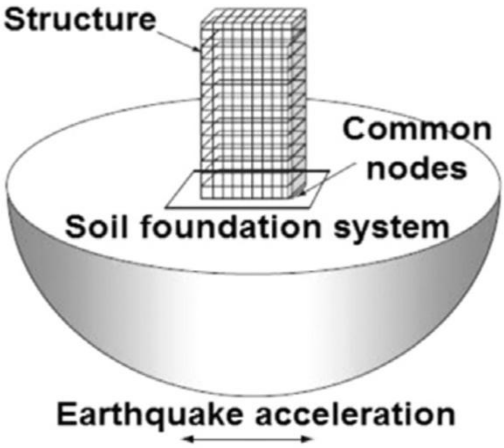


Figure 1: The soil-structure system in the Direct Method **[29]**

There is a very limited set of criteria in the seismic design codes for examining the effects of SSI. Act ATC 3-06 [30] is the first code that contains some guidelines that take into consideration the effects of the interaction in the design stage of buildings. The simplified criteria of SSI have been itemized in Acts FEMA 302 and FEMA 303 [31]. Furthermore, Chapter 19 of Standard ASCE-7 [32] treats the impacts of SSI in the seismic design of the building structures. Nonetheless, these presented criteria only consider shallow foundations while taking no notice of deep foundations.

There is no study for irregular tall buildings under near-field earthquakes including SSI effects. The present study is discussing the seismic response of a real irregular high-rise building under three altered conditions of soil which are: hard, medium and soft soil types, in order to clarify the effect of these soil types in the seismic damage of the building. Storey displacements and drifts, storey forces, base shear, spectral acceleration and spectral displacement are calculated and analyzed in order to assess and compare the different responses. A 44-storey high-rise structure is adopted for numerical studies which are performed using ETABS software [33]. The rest of the paper is organized as follow: A numerical model of the structure including SSI effects is presented, then an overview of the ground motion input characteristics is detailed. The numerical results of the structural response of the building subjected to earthquake excitations is presented and analyzed. Finally, the concluding remarks are summarized.

II. Modeling of Multi-storey Building

In the present study, the three-dimensional reinforced concrete fixed-base structure was modeled and analyzed using time history analysis. ETABS software is used to investigate the seismic response of the elastic structure including SSI effects. A 44 storeys (Figure 2) is modeled with a height of 174 m (length = 45m and width = 21m) and the international building code (IBC-2018) is taken into consideration for dynamic analysis [34]. In order to proceed with the study, the structural model is designed using shear-walls system with a damping ration equal to 5 %. The dynamic analysis is performed at each floor level, starting from the ground floor until the top storey. To perform this dynamic analysis, the following steps should be done: geometric modeling, sectional properties and material properties, supports: boundary conditions, loads and load combinations (dynamic), analysis specification and design command [33]. The response modification factor of the fixed base model is taken as the value of 4 consistent with shear wall system case. Furthermore, it is assumed that the foundation of the structures is located on three types of ground states: soft (S_e), medium (S_c) and dense (S_a), using IBC soil classification [34]. Figure 2 shows the 3D and the Etabs model of the building. A clear irregularity in the form of the building is pronounced since as mentioned the goal is to study the effect of SSI on this kind of high-rise structures, where the stiffness of the structure linearly decrease with the increase of its height. The design of structural members is performed in accordance with ACI-318-14 [35].

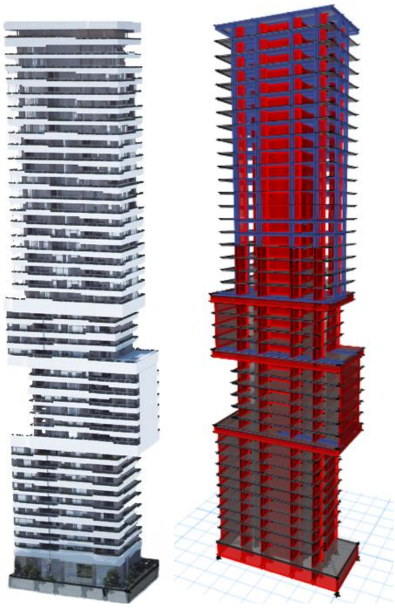
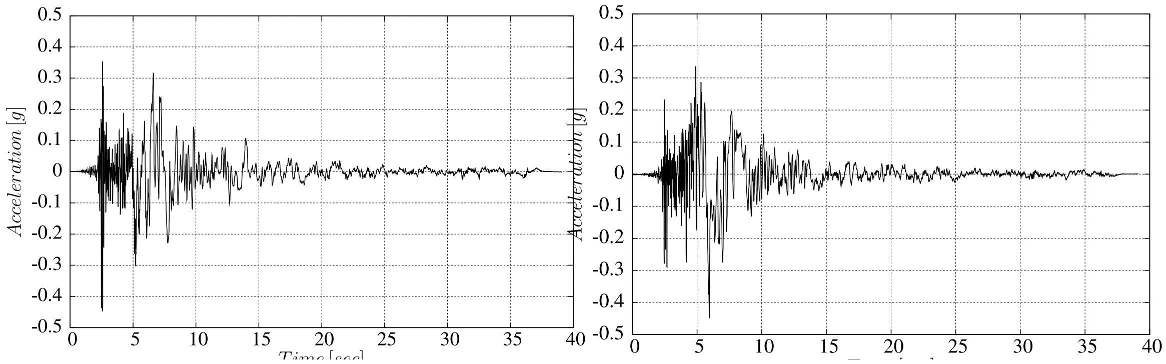

(a) 3D Model (b) ETABS Model

Figure 2: A 3D View of the irregular high-rise building.

III. Ground Motion Input Characteristics

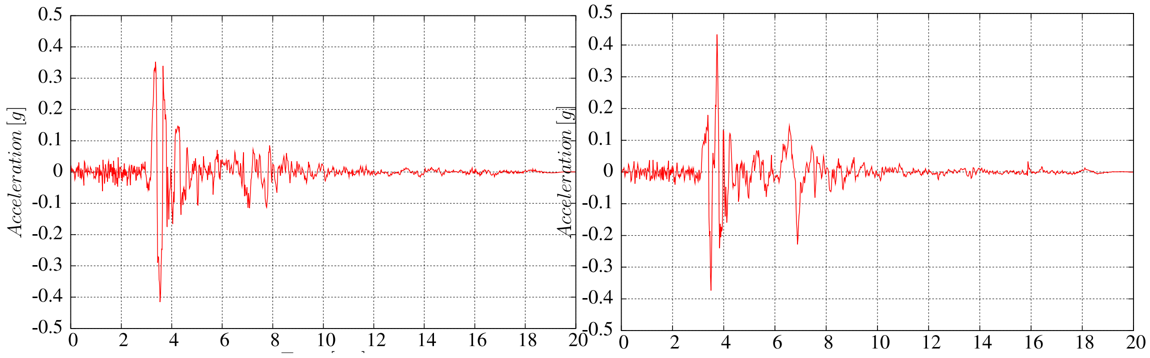
The ground accelerations generate normally the seismic forces in a structure. The simulations of time history analysis of the structure are carried out using three earthquake signals, including Tabas, Northridge and El-Centro earthquakes as shown in Figure 3, Figure 4 and Figure 5[36, p. 1], [37, p. 2]. These recorded ground motions are the most common used near-field ground motions for seismic analysis. Such type of analysis allows to understand the dynamic performance of the structure under a real earthquake strike. It has been noticed that the maximum values of spectral accelerations occur at low period values i.e. high frequencies. Therefore, buildings with a low natural period will be subject to high excitations under these seismic waves.

Figure 6shows that the response spectrum function, according to IBC [34] for various soil types, by taking into account seismic zone factors S_s=1.2, S_1=0.4 [38] and the damping ratio is 5%. The El-Centro earthquake is matched with response spectrum using time domain method (Figure 7, Figure **8** and Figure 9) [39]–[41], to consider the effect of soil in time history function. The other two earthquake signals (Northridge and Tabas) are also matched with response spectrum (presented in the Appendix A), for the three types of soil. The storey displacement, storey drift, storey shear forces, spectral acceleration and spectral displacement are calculated for each floor and the graph is plotted for each structure for the different soil types.



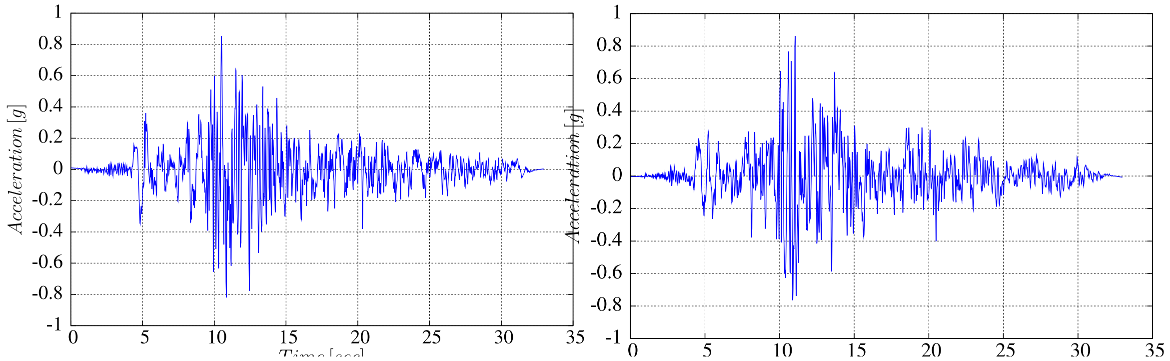
(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 3: El-Centro-Array 6 (1979) time history [36], [37].



(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 4: Northridge (1994) time history [36], [37].



(a) Acceleration in X direction(b) Acceleration in Y direction

Figure 5: Tabas (1978) time history [36], [37].

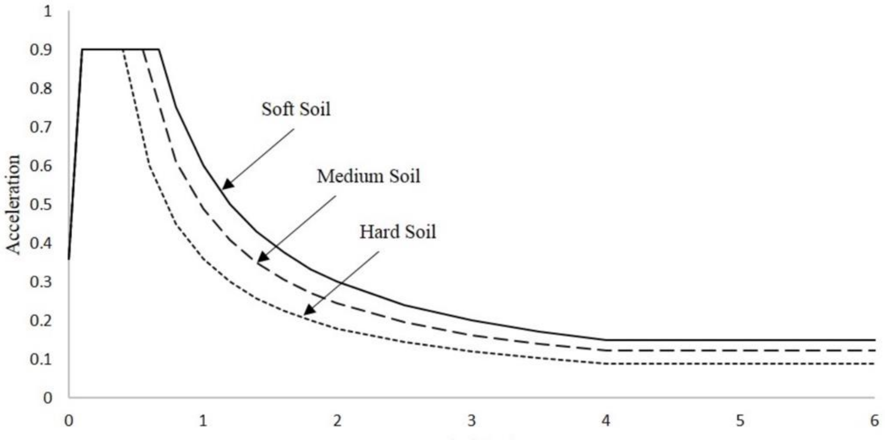
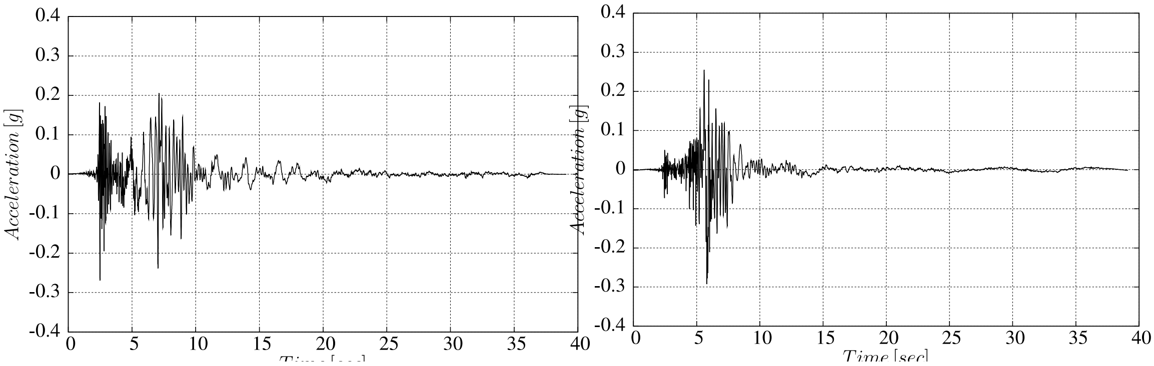
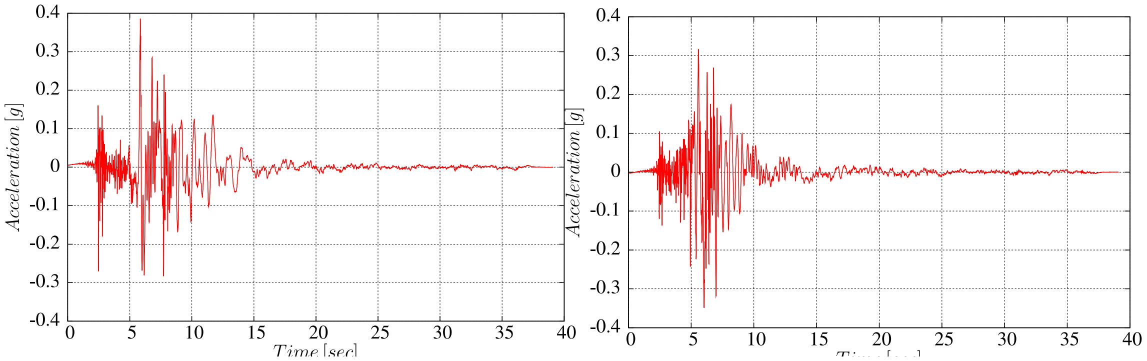


Figure 6: Response spectrum function [34].



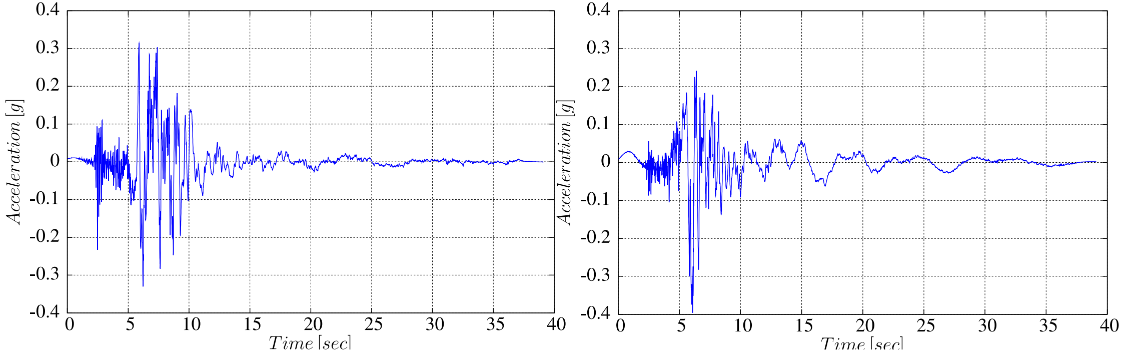
(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 7: Matched response spectrum-time history function (El-Centro 1979)-hard soil.



(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 8: Matched response spectrum-time history function (El-Centro 1979)-medium soil.



(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 9: Matched response spectrum-time history function (El-Centro 1979)-soft soil.

IV. Structural Responses

In order to reduce the structural damages of a high-rise structure, the reduction of the storeys large displacements is one of the main design goals. On the other hand, to enhance the comfort/serviceability and to reduce the non-structural damages, the reduction of maximum acceleration of storeys, especially for high-rise buildings, is a critical issue for designers. The numerical model of the building is designed by considering that the structure is totally base fixed. Then several simulations are carried out using three different earthquake excitations (El-Centro, Northridge and Tabas) and three soil types to assess the structural behavior under these multiple cases. Table 1 presents the maximum displacement calculated by time history analysis (THA) for various soil conditions according to IBC code and for both X and Y directions. It is observed that the maximum displacements at the roof are 24.58 cm, 33.55 cm and 59.15 cm for respectively hard, medium and soft soil conditions, respectively for the El-Centro earthquake case, whereas these responses are about 27.31 cm, 35.20 cm and 52.86 cm for Northridge earthquake case. As for Tabas earthquake case, the maximum displacements at roof are 25.10 mm, 31.74 cm and 45.74 cm. The results show that storey displacement decreases whenever there is an increase in the properties of soil stiffness. Hence, the increase of soil stiffness decreases the maximum displacement by 59% for El-Centro, 48% for Northridge and 45% for Tabas earthquake, from soft to hard soil condition.

Table 1: Maximum structural responses for different soil conditions

Earthquake	**SoilType**		
El-Centro		Maximum floor Displacement (cm)	
		X-direction	Y-direction
	Hard	24.58	19.75
	Medium	33.55	32.79
	Soft	36.13	59.15
Northridge		Maximum floor Displacement (cm)	
		X-direction	Y-direction
	Hard	27.31	19.64
	Medium	27.38	35.20
	Soft	44.87	52.86
Tabas		Maximum floor Displacement (cm)	
		X-direction	Y-direction
	Hard	19.98	25.10
	Medium	31.74	27.68
	Soft	45.74	40.34

The difference in lateral displacement between two successive storeys is defined as storey drift, an important factor for assessing damage in the building for a given excitation. Larges lateral forces can be exerted on structures during an earthquake; the main effects are for drifts and lateral displacements: both of structural components (such as beams and columns) and non-structural components are influenced by the movements, besides the movements influence on adjacent structures. Without correct consideration, large displacements and drifts can have negative effects. Figure 10 demonstrates the maximum drifts of storeys during the three earthquakes. It is noticed that the storey drift decreases according to the soils flexibility. Thus, the largest drifts were created in soft soil condition. The building discontinuities appear clearly in the drifts curves. Therefore, the bi-directional excitation is necessary in such type of building where the dynamic behavior extremely differs between its two directions. The results show that the time responses of the structure are significantly affected by the soil type. In other words, ignoring the SSI impacts may result in an unrealistic and inappropriate assessment of the seismic responses of high-rise structures. It can be observed that the increase of soil stiffness mitigates the seismic responses in terms of peak floor displacement and drift. The degree of mitigation depends also on the excitation properties [42], [43].

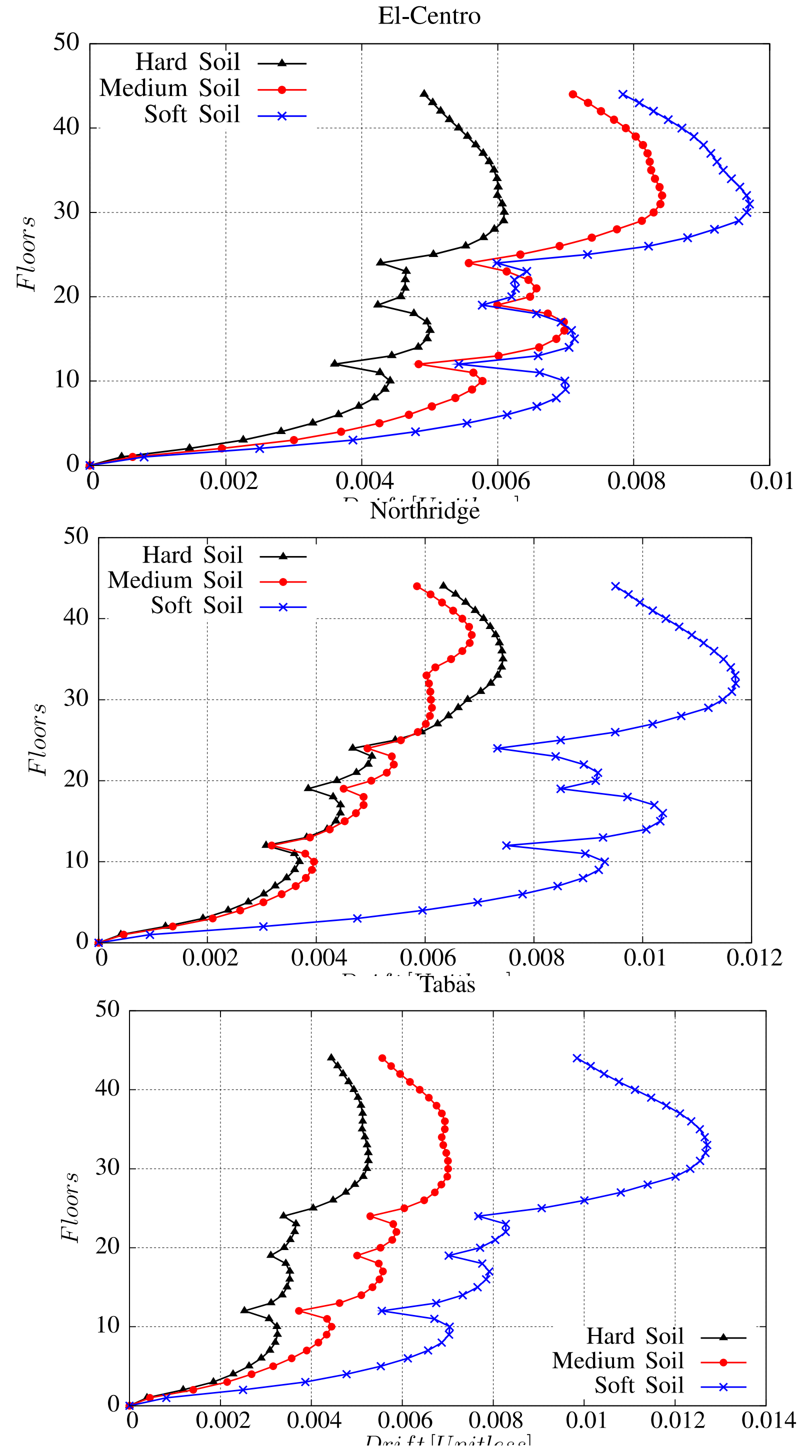


Figure 10: The maximum drift ratio of floors during El-Centro, Northridge and Tabas earthquakes.

V. Storey forces

Storey force is the distribution of designed lateral base shear force at all levels above the ground. Storey force value, as per IBC code, is calculated for buildings with different heights and soil types. Figure 11 shows the variations in the pattern of distribution of lateral shear force in a 44-storey building corresponding to the seismic provisions of IBC code. The results demonstrate that the value of storey shear increases when the stiffness of the soil decreases, this observation is the same for the three earthquake signals. The storey shear value is the highest for the soft soil type (S_e) and the lowest for hard soil type (S_a). The mass discontinuities are also presented clearly in Figure 11. Except El-Centro excitation, the shear forces for medium and hard soil seems to be almost equal. It means for these excitations and above a specific value of soil stiffness, the values of shear forces will remain stable (Figure 12).

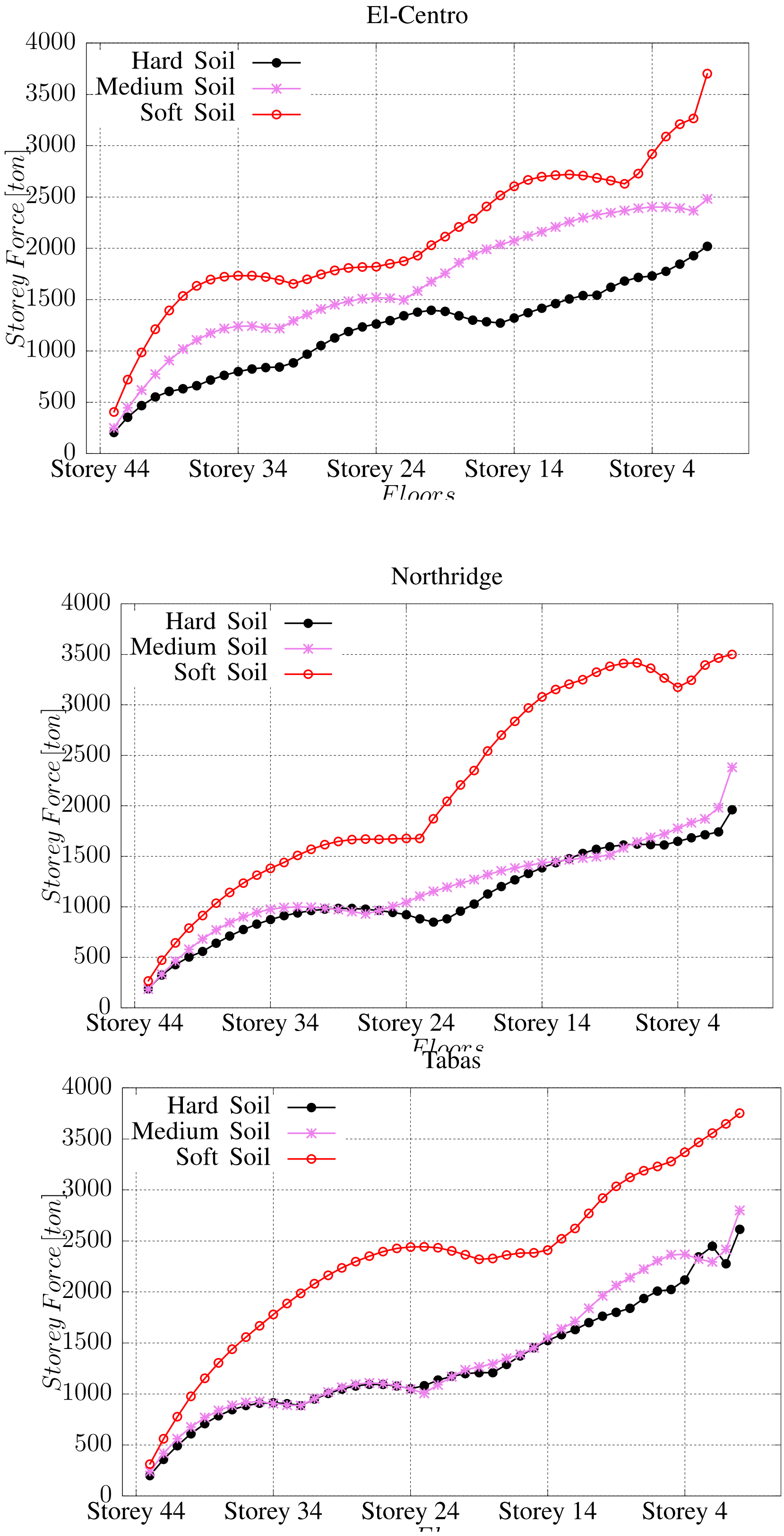


Figure 11: Storey forces during El-Centro, Northridge and Tabas earthquakes.

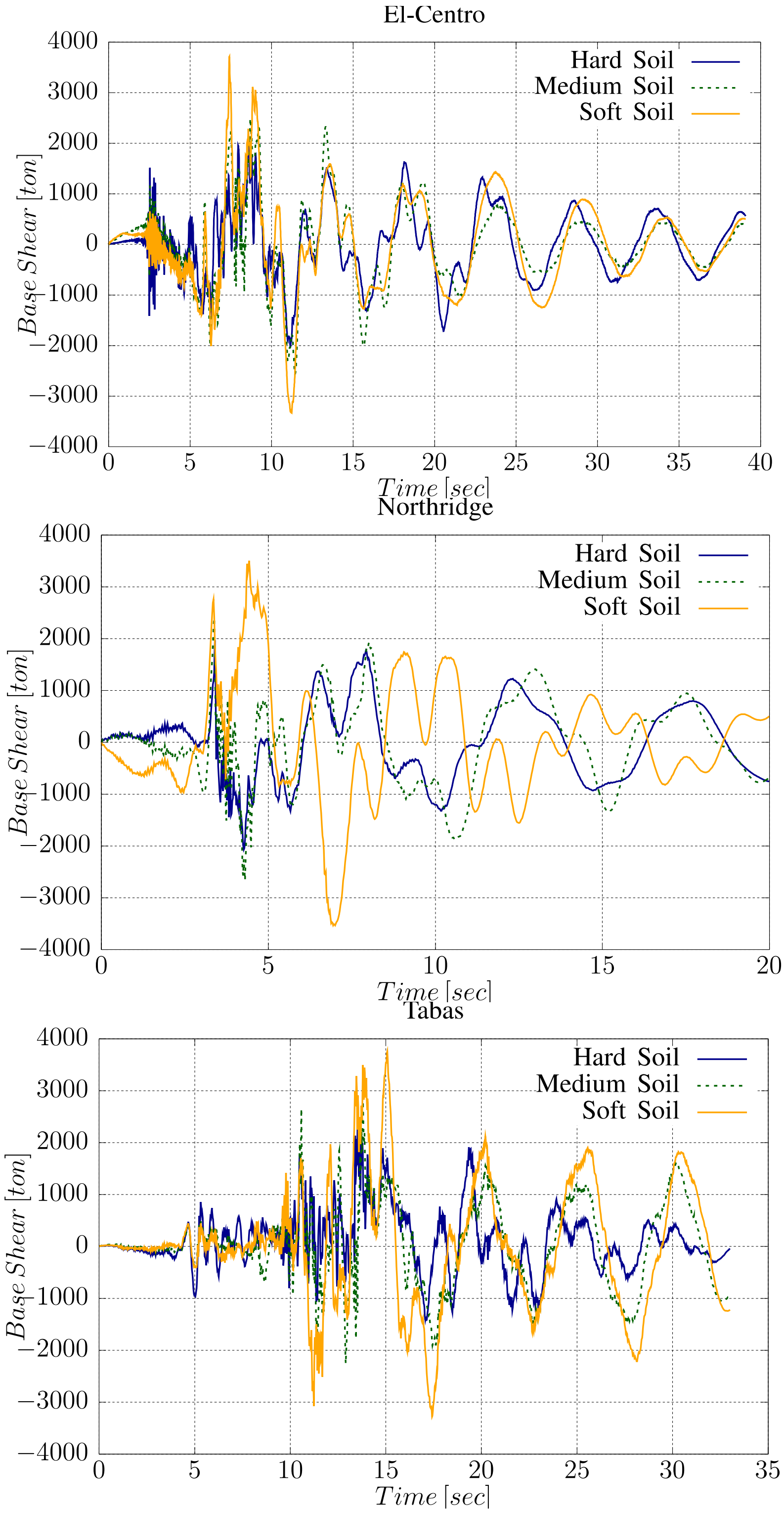


Figure 12: Time history base shear during El-Centro, Northridge and Tabas earthquakes.

VI. Time history of base shear

The base shear force depends directly on the input earthquake history and the soil type specially its damping properties. Since the base shear is distributed over the floors, the structural system should be able to resist it. Whatever it is, the building must be designed to avoid the risk of structural failure regarding the high or the low structural base shear. The most important is that your structure is well designed to resist it or not. The calculations of base shear (V) depend on:

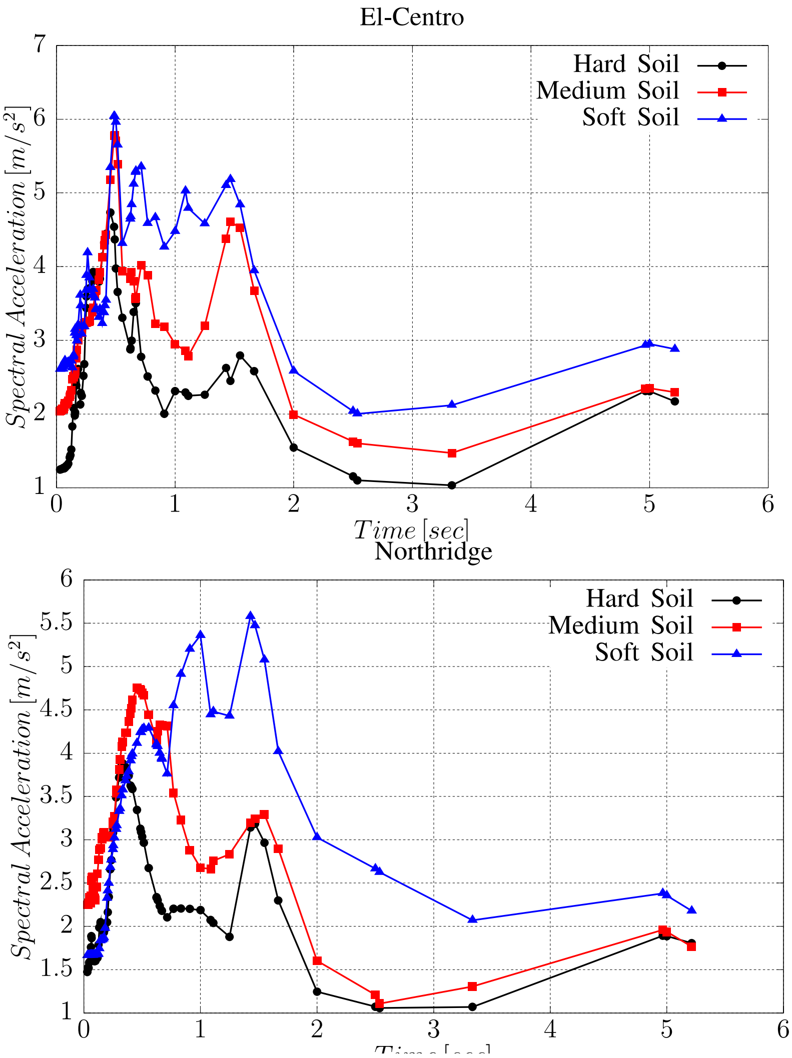
- The soil type.

- The building proximity to potential sources of seismic activity (near fault and far fault earthquakes).
- The possibility of significant seismic ground motion creation.
- The level of ductility and over-strength of the building structural configurations and the structural total weight.

Figure 12 presents the values of base shear over S_a, S_c, and S_e soil conditions for the three earthquake excitations. The soil condition has noticeable effects on the base shear variation. As presented in Figure 12, it is noticed that the percentage reduction of base shear values obtained by considering the hard soil condition is 27% when it is compared to the one of the medium soil type, and 41% when compared to the one of the soft soil type, as average of the three excitations. Among the considered soil conditions, it is found that the hard soil condition produces less base shear of the buildings.

VII. Spectral Acceleration at Roof

The Peak ground acceleration (PGA) is the maximum ground acceleration that occur during an excitation. In other words, it is the amplitude of the largest absolute acceleration recorded on an accelerogram during an earthquake. PGA is divided into horizontal and vertical components since the earthquakes usually occur in all three directions [44]. The horizontal components are generally larger than the components in the vertical direction. Thus, the peak horizontal acceleration is the most used type of ground acceleration in building design. In this work, the maximum values of horizontal spectral acceleration for the three excitations are shown in Figure 13 taking intoconsideration the different soil types. The maximum values of spectral acceleration during El-centro excitation are: 4.73 m/s^2, 5.78 m/s^2 and 6.04 m/s2 respectively for hard, medium and soft soil. In the case of Northridge excitation, the values are 3.88 m/s^2, 4.75 m/s^2 and 5.58 m/s^2, respectively. For Tabas excitation, these values are 4.80 m/s^2, 6.19 m/s^2 and 6.68 m/s^2, respectively. The results show that higher spectral accelerations are produced in soft soil conditions when compared to medium and hard soil conditions.



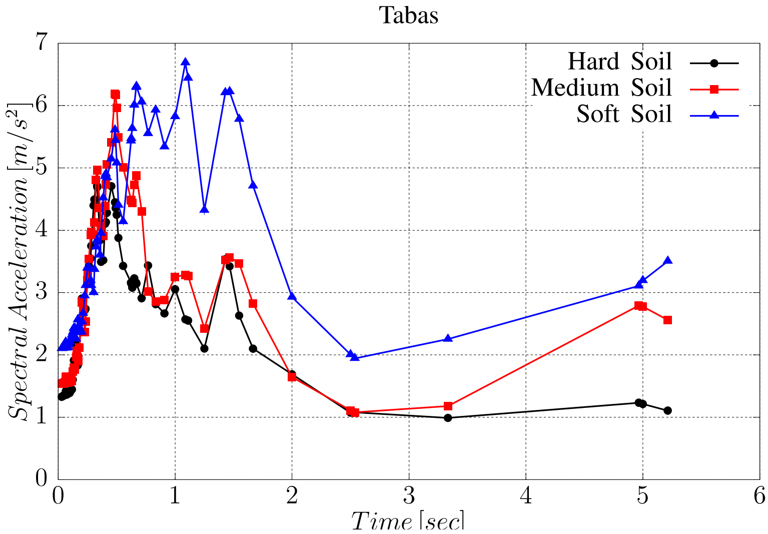
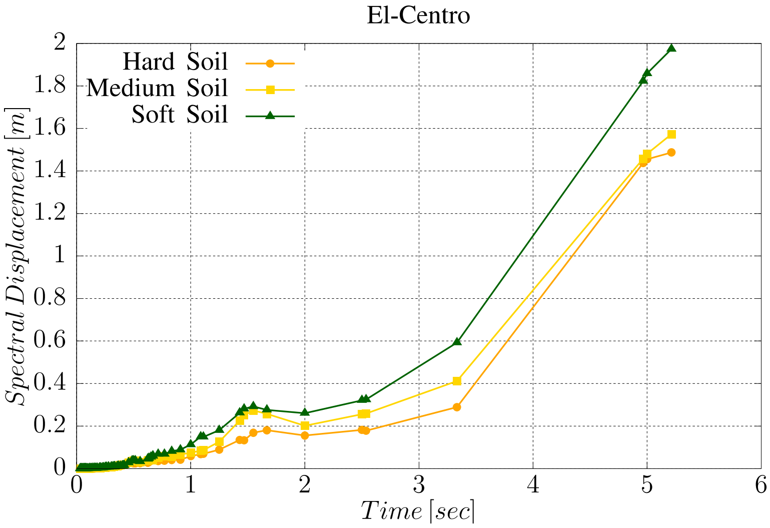


Figure 13: Spectral acceleration in various soil conditions during El-Centro, Northridge and Tabas earthquakes.

VIII. Spectral Displacement at Roof

Figure 14presents the time history of the spectral displacement at the roof for the three earthquakes, matched with the response spectrum. The peak spectral displacements at the roof show that higher displacement in soft soil condition is obtained. It is less than the spectral displacement values of medium and hard soil condition. Therefore, as an average for the three earthquakes the increase in percentage of spectral displacement in soft soil condition is 37%, and 22% in medium soil condition, compared with hard soil condition. The difference in spectral displacement history of hard and medium soil condition, between El-Centro and Northridge excitations, is negligible.



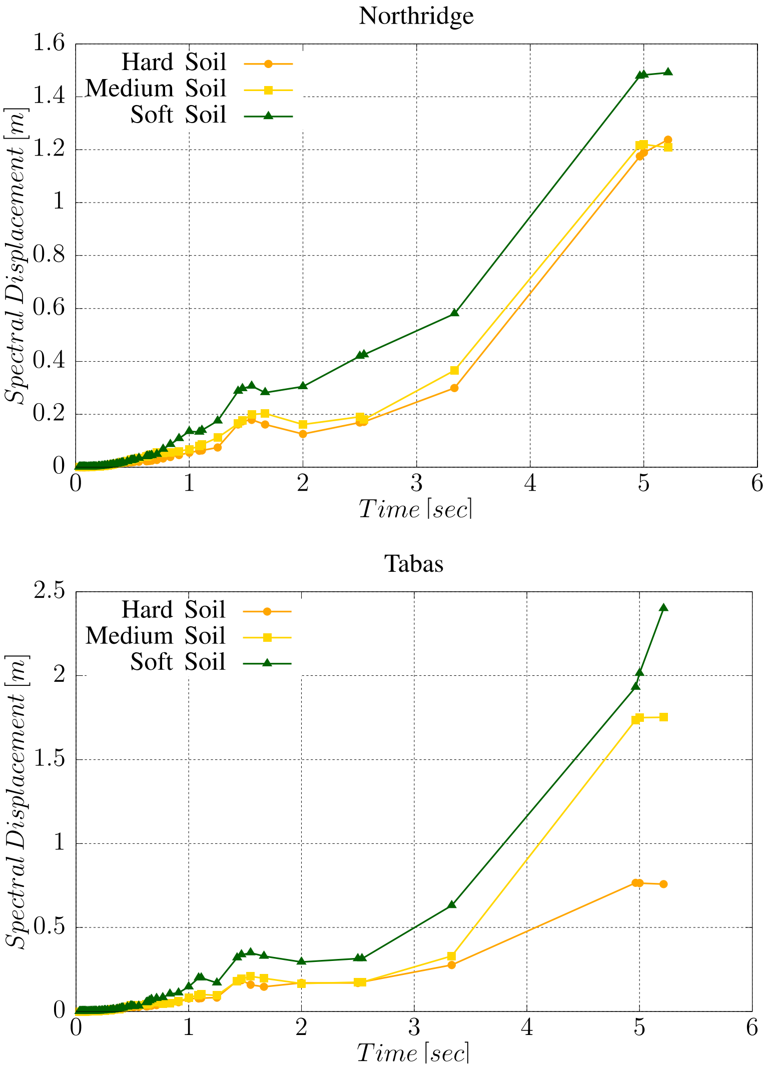


Figure 14: Spectral displacement in various soil conditions during El-Centro, Northridge and Tabas earthquakes.

IX. Conclusion

A tall building of 44 storeys has been analyzed for hard, medium and soft soil conditions. The aim of the study was to investigate the seismic performance of a fixed base building under various soil conditions according to IBC code. The structural responses of the building, such as storey displacements, storey drifts, storey forces, base shear, roof spectral acceleration and roof spectral displacement have been studied. Time history analysis was carried out by ETABS software during three earthquakes (El-Centro, Northridge and Tabas) which are matched with response spectrum by time domain method. After the analysis of the model, it can be concluded the following:

- The value of storey shear increases with the decrease of soil stiffness; it is the highest for the soft soil type (Se) and the lowest for hard soil type (Sa).
- The roof spectral acceleration history (PGA) increases by 48.7 % for soft soil condition and by 40.5\% for medium soil condition, when compared to the hard soil condition.
- The storey displacement increases with the increase of soil flexibility; the largest displacement is produced in soft soil conditions compared to hard and medium soil.
- The storey drift increases with the increase of soil flexibility. In other words, the largest drifts are produced in soft soil condition.
- Hard and medium soil conditions are more suitable for high-rise structures.

Funding Statement: No specific funding for this study

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

References

[1]. A. R. Dexter, "Advances in characterization of soil structure," *Soil and Tillage Research*, vol. 11, no. 3, pp. 199–238, 1988, doi: https://doi.org/10.1016/0167-1987(88)90002-5.

[2]. E. Kausel, "Early history of soil–structure interaction," *Soil Dynamics and Earthquake Engineering*, vol. 30, no. 9, pp. 822–832, 2010, doi: https://doi.org/10.1016/j.soildyn.2009.11.001.

[3]. J. Zhou, C. Sun, X. Dai, and G. Chen, "Seismic Reliability Assessment of Inelastic SDOF Systems Subjected to Near-Fault Ground Motions Considering Pulse Occurrence," *Structural Durability \& Health Monitoring*, vol. 13, no. 4, 2019, doi: 10.32604/sdhm.2019.05171.

[4]. Z. Chen, W. Wang, and D. Li, "Instability Analysis of Strike-Slip Fault Based on Cusp Catastrophe Model," *Structural Durability \& Health Monitoring*, vol. 12, no. 1, 2018, doi: 10.3970/sdhm.2018.012.019.

[5]. A. S. Veletsos and P. M. Anumolu, "Seismic Interaction of Structures and Soils: Stochastic Approach," *Journal of Structural Engineering*, vol. 115, no. 4, pp. 935–956, 1989, doi: 10.1061/(ASCE)0733-9445(1989)115:4(935).

[6]. J. Liu, L. Zhang, H. Zhang, and T. Liu, "Seismic Vulnerability Analysis of Single-Story Reinforced Concrete Industrial Buildings with Seismic Fortification," *Structural Durability \& Health Monitoring*, vol. 13, no. 2, 2019, doi: 10.32604/sdhm.2019.04486.

[7]. A. Alonso-Rivers and R. Salgado-Estrada, "Dynamic Simulation of Cracked Buildings for Damage Detection," *Structural Durability \& Health Monitoring*, vol. 14, no. 3, 2020, doi: 10.32604/sdhm.2020.010743.

[8]. V. Reissner, "Stationäre, axialsymmetrische, durch eine schüttelnde masse erregte schwingungen eines homogenen elastischen halbraumes," *Ingenieur-Archiv*, vol. 7, no. 6, pp. 381–96., 1936.

[9]. D. W. Taylor, *Fundamentals of soil mechanics*. New York: Wiley, 1964.

[10]. Y. Ohsaki, "Effects of Local Soil Conditions upon Earthquake Damage," in *Soil Dynamics Specialty Session, Seventh International Conference on Soil Mechanics and Foundation Engineering*, Mexico city, 1969, pp. 3–32.

[11]. B. Ghosh and S. Madabhushi, "Effects of localised soil inhomogeneity in modifying seismic soil structure interaction," in *Proceeding of ASCE 16th engineering mechanics conference*, Seattle, Jul. 2003, pp. 1–8.

[12]. A. S. Veletsos and J. W. Meek, "Dynamic behaviour of building-foundation systems," *Earthquake Engineering & Structural Dynamics*, vol. 3, no. 2, pp. 121–138, 1974, doi: 10.1002/eqe.4290030203.

[13]. J. P. Wolf and C. Song, "Some cornerstones of dynamic soil–structure interaction," *Engineering Structures*, vol. 24, no. 1, pp. 13–28, 2002, doi: https://doi.org/10.1016/S0141-0296(01)00082-7.

[14]. M. Htwe, "Uncertainty and soil-structure interaction effects on the seismic response evaluations of base isolated bridge structures," PhD Thesis, Graduate school of Science and Engineering, Kagoshima University, 2005.

[15]. A. M. Mwafy, O. Kwon, and A. S. Elnashai, "Inelastic Seismic Response of a 59-Span Bridge with Soil-Structure Interaction," Beijing, china, 2007.

[16]. M. Ciampoli and P. Pinto, "Effects of Soil-Structure Interaction on Inelastic Seismic Response of Bridge Piers," *Journal of Structural Engineering*, vol. 121, no. 5, pp. 806–814, 1995, doi: 10.1061/(ASCE)0733-9445(1995)121:5(806).

[17]. J. Avilés and L. E. Pérez-Rocha, "Soil–structure interaction in yielding systems," *Earthquake Engineering & Structural Dynamics*, vol. 32, no. 11, pp. 1749–1771, 2003, doi: 10.1002/eqe.300.

[18]. S. L. Kramer and others, *Geotechnical earthquake engineering*. Upper Saddle River, New Jersey: Prentice-Hall Inc., 1996.

[19]. M. Moghaddasi, M. Cubrinovski, J. G. Chase, S. Pampanin, and A. Carr, "Probabilistic evaluation of soil–foundation–structure interaction effects on seismic structural response," *Earthquake Engineering & Structural Dynamics*, vol. 40, no. 2, pp. 135–154, 2011, doi: 10.1002/eqe.1011.

[20]. E. Sáez, F. Lopez-Caballero, and A. Modaressi-Farahmand-Razavi, "Effect of the inelastic dynamic soil–structure interaction on the seismic vulnerability assessment," *Structural Safety*, vol. 33, no. 1, pp. 51–63, 2011.

[21]. P. Rajeev and S. Tesfamariam, "Seismic fragilities of non-ductile reinforced concrete frames with consideration of soil structure interaction," *Soil Dynamics and Earthquake Engineering*, vol. 40, pp. 78–86, 2012, doi: https://doi.org/10.1016/j.soildyn.2012.04.008.

[22]. K. D. Pitilakis, S. T. Karapetrou, and S. D. Fotopoulou, "Consideration of aging and SSI effects on seismic vulnerability assessment of RC buildings," *Bulletin of Earthquake Engineering*, vol. 12, no. 4, pp. 1755–1776, 2014, doi: 10.1007/s10518-013-9575-8.

[23]. A. Gomez Masso, J. Lysmer, J. C. Chen, and H. B. Seed, "Soil structure interaction in different seismic environments, Report of Earthquake Engineering Research Center," University of California, Berkeley, UCB/EERC-79/18, Aug. 1979.

[24]. S. Gupta and N. S. Foundation (U.S.), *Hybrid Modelling of Soil-structure Interaction*. University of California, Earthquake Engineering Research Center, 1980.

[25]. J. P. Wolf, "Soil-structure-interaction analysis in time domain," *Nuclear Engineering and Design*, vol. 111, no. 3, pp. 381–393, 1989, doi: https://doi.org/10.1016/0029-5493(89)90249-5.

[26]. G. George, "Formulas and Charts for Impedances of Surface and Embedded Foundations," *Journal of Geotechnical Engineering*, vol. 117, no. 9, pp. 1363–1381, 1991, doi: 10.1061/(ASCE)0733-9410(1991)117:9(1363).

[27]. NISTGCR, "Soil-structure interaction for building structures," U.S. Department of Commerce, 12-917–21, Sep. 2012.

[28]. J. Yang, J. B. Li, and G. Lin, "A simple approach to integration of acceleration data for dynamic soil–structure interaction analysis," *Soil Dynamics and Earthquake Engineering*, vol. 26, no. 8, pp. 725–734, 2006, doi: https://doi.org/10.1016/j.soildyn.2005.12.011.

[29]. N. Yeganeh, J. B. Bazaz, and A. Akhtarpour, "Seismic analysis of the soil–structure interaction for a high rise building adjacent to deep excavation," *Soil Dynamics and Earthquake Engineering*, vol. 79, pp. 149–170, 2015, doi: https://doi.org/10.1016/j.soildyn.2015.08.013.

[30]. ATC, *Tentative Provisions for the Development of Seismic Regulations for Buildings: A Cooperative Effort with the Design Professions, Building Code Interests, and the Research Community*. Washington D.C.: Applied Technology Council, 1978.

[31]. NEHRP, *NEHRP recommended provisions for seismic regulations for new buildings and other structures, FEMA 303, 302*. Council, Building Seismic Safety, 1997.

[32]. ASCE, *Minimum Design Loads for Buildings and Other Structures*. American Society of Civil Engineers, ASCE/SEI 7-10, 2013. doi: 10.1061/9780784412916.

[33]. CSI, *CSI analysis reference manual*. Computers and Structures inc, Berkeley, 2013.

[34]. A. Douglas W. Thornburg, S. Chris Kimball, and P. William C. Bracken, *2018 International Building Code Illustrated Handbook*. New York: McGraw-Hill Education, 2018.

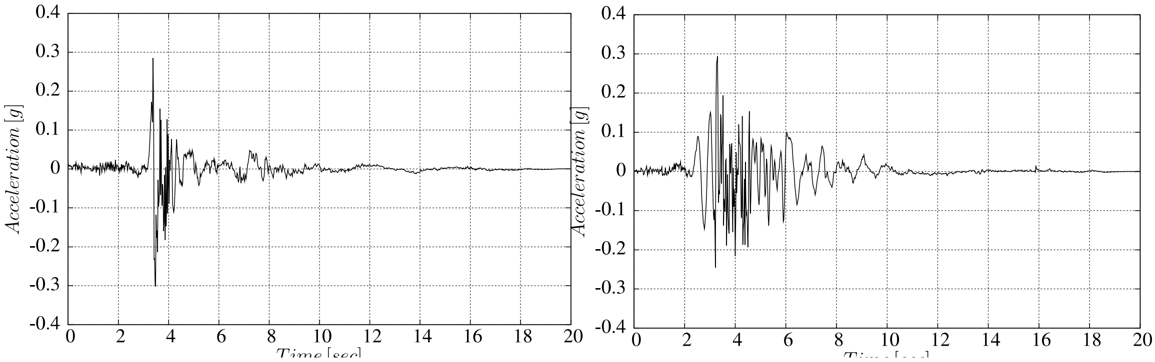
[35]. ACI, *ACI Committee 318, Building code requirements for structural concrete: (ACI 318-95); and commentary (ACI 318R-95)*. Farmington Hills, MI : American Concrete Institute, 1995.

[36]. K. W. Campbell and Y. Bozorgnia, "A Ground Motion Prediction Equation for the Horizontal Component of Cumulative Absolute Velocity (CAV) Based on the PEER-NGA Strong Motion Database, PEER Review No. 2010/01, Pacific Earthquake Engineering Research Center, University of Califonia, Berkley," *Earthquake Spectra*, vol. 26, pp. 635–650, 2010.

[37]. K. Campbell and Y. Bozorgnia, "Cumulative absolute velocity (CAV) and seismic intensity based on the PEER-NGA database, Pacific Earthquake Engineering Research Center, University of Califonia, Berkley," *Earthquake Spectra*, vol. 28, pp. 457–485, 2012, doi: 10.1193/1.4000012.
[38]. Lebanese Seismic Norms, NL135, *Protection from earthquakes: general rules*. S. I. LIBNOR, Ed., Lebanon, 2012.
[39]. VDC, *Strong-Motion Virtual Data Center (VDC)*. Global component of the center for engineering strong motion data, 2014. [Online]. Available: https://stron gmotioncenter.org/vdc/scripts/earthquakes.plx
[40]. F. Naeim and M. Lew, "On the Use of Design Spectrum Compatible Time Histories," *Earthquake Spectra*, vol. 11, no. 1, pp. 111–127, 1995, doi: 10.1193/1.1585805.
[41]. A. E. Seifried and J. Baker, "Spectral variability and its relationship to structural response estimated from scaled and spectrum-matched ground motions," *Earthquake Spectra*, vol. 32, pp. 2191–2205, 2016, doi: 10.1193/061515EQS094M.
[42]. A. Hassan and S. Pal, "Effect of soil condition on seismic response of isolated base buildings," *International Journal of Advanced Structural Engineering*, vol. 10, no. 3, pp. 249–261, 2018, doi: 10.1007/s40091-018-0195-z.
[43]. S. Etedali, M. Akbari, and M. Seifi, "MOCS-based optimum design of TMD and FTMD for tall buildings under near-field earthquakes including SSI effects," *Soil Dynamics and Earthquake Engineering*, vol. 119, pp. 36–50, 2019, doi: https://doi.org/10.1016/j.soildyn.2018.12.027.
[44]. S. Prayag and R. Keri, "Comparative Evaluation of Base-Isolated and Fixed-Base Buildings Using a Comprehensive Response Index," *Journal of Structural Engineering*, vol. 135, no. 6, pp. 698–707, Aug. 2020, doi: 10.1061/(ASCE)0733-9445(2009)135:6(698).

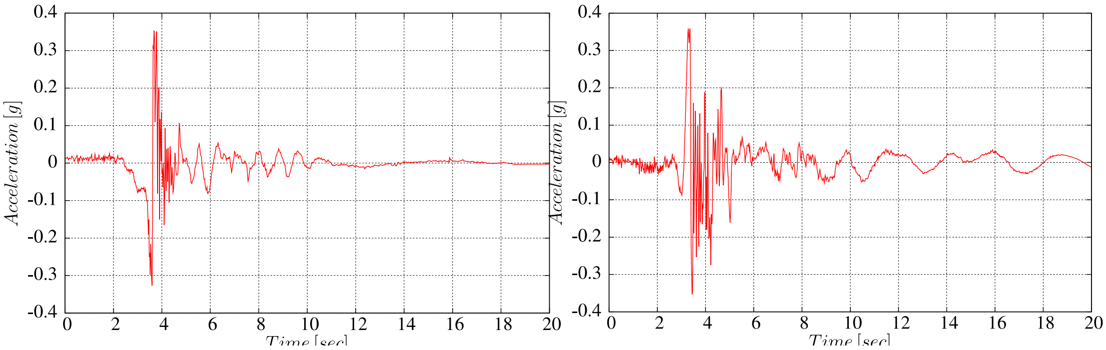
Appendix A.

In this Appendix, the earthquake signals (Northridge and Tabas) which are matched with response spectrum using time domain method are presented, considering the effect of the three soil types in time history function in Figure 15: Matched response spectrum-time history function (Northridge 1994)-hard soil., Figure 16, Figure 17, Figure 18, Figure 19 and Figure 20.



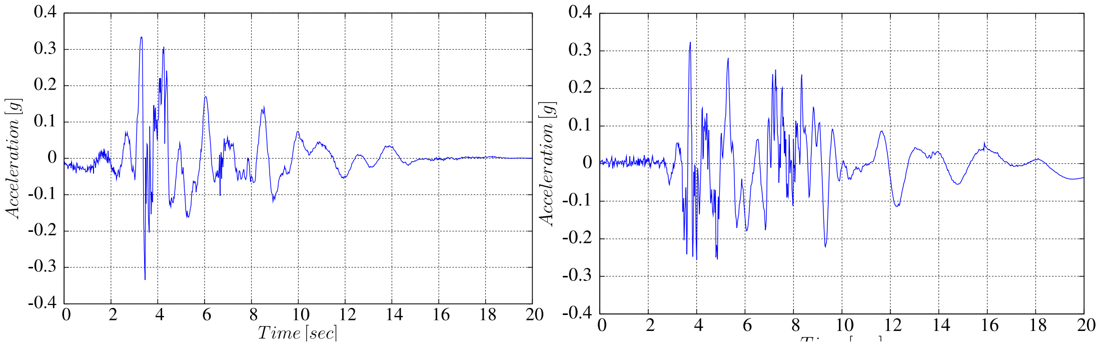
(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 15: Matched response spectrum-time history function (Northridge 1994)-hard soil.



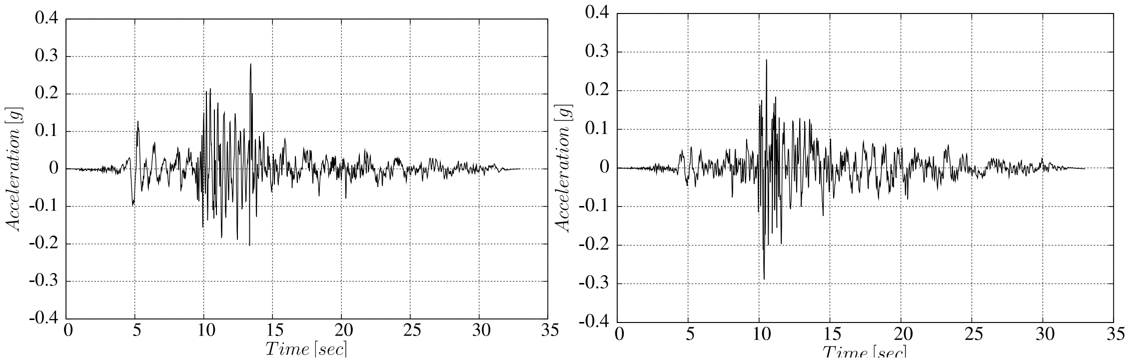
(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 16: Matched response spectrum-time history function (Northridge 1994)-medium soil.



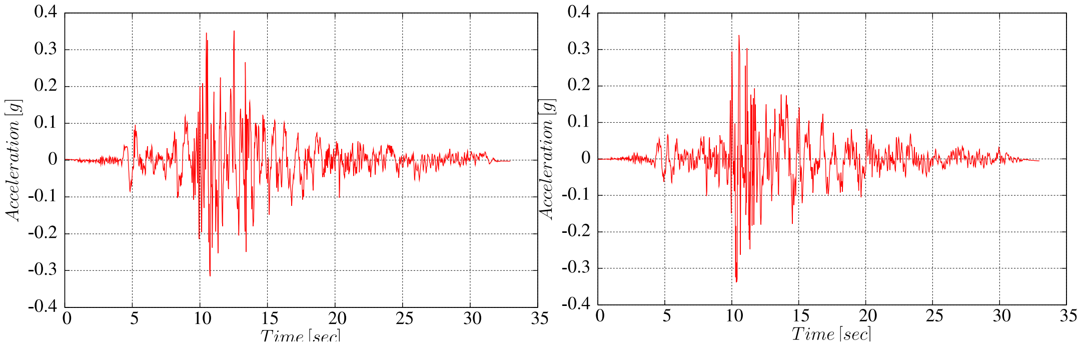
(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 17: Matched response spectrum-time history function (Northridge 1994)-soft soil.



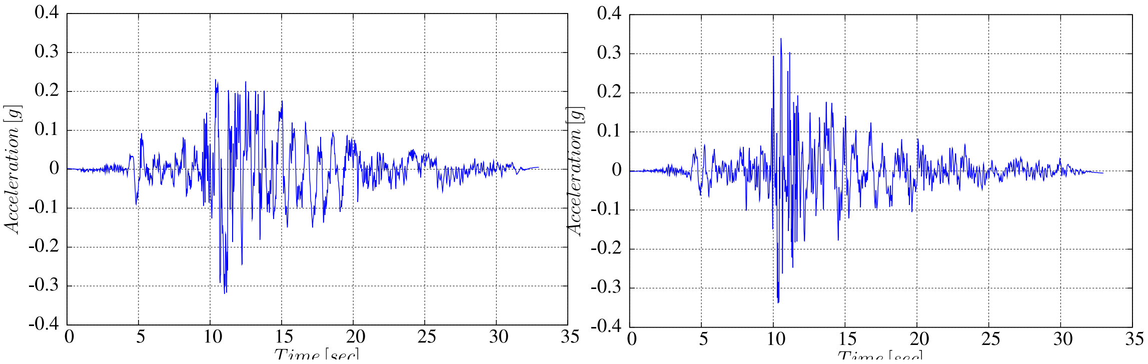
(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 18: Matched response spectrum-time history function (Tabas 1978)-hard soil.



(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 19: Matched response spectrum-time history function (Tabas 1978)-medium soil.



(a) Acceleration in X direction (b) Acceleration in Y direction

Figure 20: Matched response spectrum-time history function (Tabas 1978)-soft soil.