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Influence of Soil Structure Interaction on Seismic Response of Multi-Storey Buildings

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ABSTRACT
In the seismic analysis of a structure resting on the ground, the response of the sub-soil affects the response of the structure and vice versa. Also, the structure displacements and the ground displacements are not independent of each other. This phenomenon is called soil-structure interaction (SSI). In this study, to evaluate the effects of SSI on seismic response of multi-storey buildings, three dimensional analyses were performed on moment-resisting frames resting on different soil types with different shear wave velocities and shear moduli, representing soil classes: B, C, and D according to ECP (201, 2011). Three structural models, consisting of five, eight, and ten storey models, have been analyzed using ABAQUS software under two base conditions: fixed base condition, and flexible base condition "considering SSI effects". Two ground motions (El Centro 1940, and Kobe 1995) have been chosen for the required analysis. The results of the selected cases indicate that base shear forces generally decrease by decreasing the shear wave velocity and shear modulus of the subsoil. Thus, considering SSI effects in the seismic analysis of moment-resisting frames is essential to guarantee both economical and safe design of multi-storey buildings.

Keywords: *Soil structure interaction; Dynamic analysis; ABAQUS; Moment resisting frames; Time history analysis.*

1. Introduction

To explore the effects of soil structure interaction on the seismic performance of structures, numerical and experimental methods are generally used. For experimental tests, soil structure interaction systems are difficult to be tested in full size under earthquake excitations, including both structure and soil, because of the required size and power of the testing facilities. SSI systems are commonly tested in a quite small-scale model in laboratory, the subsoil medium is usually represented by laminar shear box with soil in it, and the structure is scaled to a smaller size (often scaled to 1/30 or even smaller) or a simple cantilever mass [1-2]. This scaling procedure leads to a decrease in the analysis accuracy due to size effects. On the other side, the great progress in the field of computers and their computational powers has made the use of numerical methods, including finite element method (FEM), more popular for studying SSI problems.
In finite element method (FEM), elements stiffness matrices are often combined into a large global stiffness matrix. By employing numerical methods, researchers were able to model complex geometries and properties of soil with a high degree of accuracy. In addition, Lu et al. [3] discussed the reliance on computer simulations in the analysis of seismic ground response and they showed that challenges in this field are being gradually overcome.
Ramadan et al. [4] used analytical methods to investigate the seismic soil-structure interaction (SSI) effects on the structural response. Two-dimensional models of moment-resisting frames with variable heights (7, 10, 14, and 18 floors) are analyzed using OPENSEES program. The results showed that ignoring SSI results in underestimation of the fundamental period and overestimation of base shear forces of the analyzed structures.
Tabatabaiefar et al. [5] carried out a time history analysis for a ten-story moment-resisting frame in conjunction with three different soil types. They used Mohr-Coulomb model as the constitutive model to simulate the soil behavior. The two-dimensional model was analyzed using FLAC 2D software under two base conditions: fixed-base condition (no SSI), and flexible-base condition (considering SSI phenomenon). The results showed that base shear forces of the flexible-base condition were generally less than those of the fixed-base condition. Moreover, increasing soil flexibility resulted in a decrease in generated base shear forces.

In this study, three dimensional models of moment-resisting frames have been analyzed using ABAQUS software under two base conditions: fixed-base condition, and flexible-base condition. Three soil types with different shear moduli, and shear wave velocities have been utilized to investigate the effect of soil flexibility on seismic response of the studied structures. The effect of structure height on the system response was also investigated by analyzing three models of five, eight, and ten-storey buildings. Considering the subsoil flexibility resulted in a decrease in base shear forces, and the reduction ratio of base shear forces increased with the increase of this flexibility.

2. Research Significance

In the analysis and design process of structures resting on the ground, Flexibility of underlying soil is commonly neglected and the base of the structure is assumed to be fixed. This assumption can be a good approximation for structures resting on hard soils. However, this assumption will not be reasonable for soft soils. In the last few decades, it has been well established that SSI Phenomenon can greatly alter the response of structures subjected to seismic excitations. This study aims to investigate SSI effects on the seismic response of multi-story buildings in terms of induced base shear forces.

3. Kinematic and Inertial Effects

Soil structure interaction phenomenon can be classified into two basic divisions; kinematic interaction, and inertial interaction. Earthquake excitations cause soil medium to be deformed, which is termed as free field motion. If this earthquake excitation acts on a soil structure system, the relatively rigid foundation of the structure will not be able follow the subsoil displacement "free field motion". This deviation between foundation motion and the free field motion causes the kinematic interaction. On the other side, inertial forces are transmitted from the superstructure mass to the underlying soil, causing further deformation in the soil that is known as inertial interaction [6].

4. Equations of Motion

If the soil structure interaction is not considered, the equation of the motion for the structure under the seismic excitation can be written in the following form:

$$[M]\{\ddot{u}(t)\} + [C]\{\dot{u}(t)\} + [K]\{u(t)\} = -[M]\{\ddot{u}_g(t)\} \quad (1)$$

Where [M], [C], and [K] are mass, damping and stiffness matrices, respectively. $\{u(t)\}, \{\dot{u}(t)\}$ and $\{\ddot{u}(t)\}$ are the total displacement, velocity, and acceleration vectors of the system, and $\{\ddot{u}_g(t)\}$ is the acceleration vector of the free-field ground excitation.

On the other side, considering SSI affects leads to more complex equations that need a powerful computational tool to be solved. The two basic approaches used to solve soil structure interaction problems are the direct approach, and the substructure approach.

(A) Direct Approach

Direct approach is a method in which the entire soil structure system is modelled in a single step accounting for both kinematic and inertial interactions. Superstructure, foundation, and a part of adjacent soil medium are modeled together. Thus, the computational cost for the total system is generally too high. Using direct method requires a computer program that is able to treat both soil and structure behaviors simultaneously [7]. Hence, finite element software "ABAQUS" is utilized to solve complex equations for the soil structure system. The nonlinear material behavior for both soil and reinforced concrete can be taken into consideration using this method. Accordingly, this method was adopted in many recent studies [8, 9] for the analysis of SSI complex problems benefiting from the growing computational efficiency in most modern computers.

(B) Substructure Approach

Substructure approach is a method in which the soil structure system is broken down into two or more substructures. This method is based on the principle of superposition. Each part of the system is modeled individually and is connected to the total system through the interface with other parts. This assumption makes the substructure approach limited for linear systems only [10]. However, the substructure method can remarkably decrease the computational cost.

5. Idealization of Soil Structure System

In this study, three structural models with different heights have been selected along with three types of soils for the time history analysis. Direct method, which evaluates the entire soil structure system response in a single step, is employed in this study to get a more realistic behavior for the system compared to the substructure method. Using ABAQUS software, three dimensional models are used, as shown in Figure (1), to get more accurate results in comparison with simplified two-dimensional models.

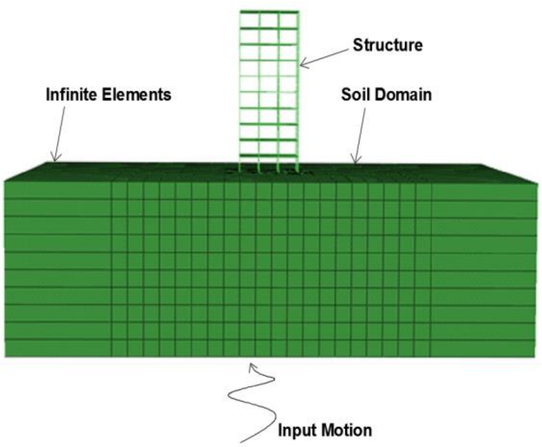
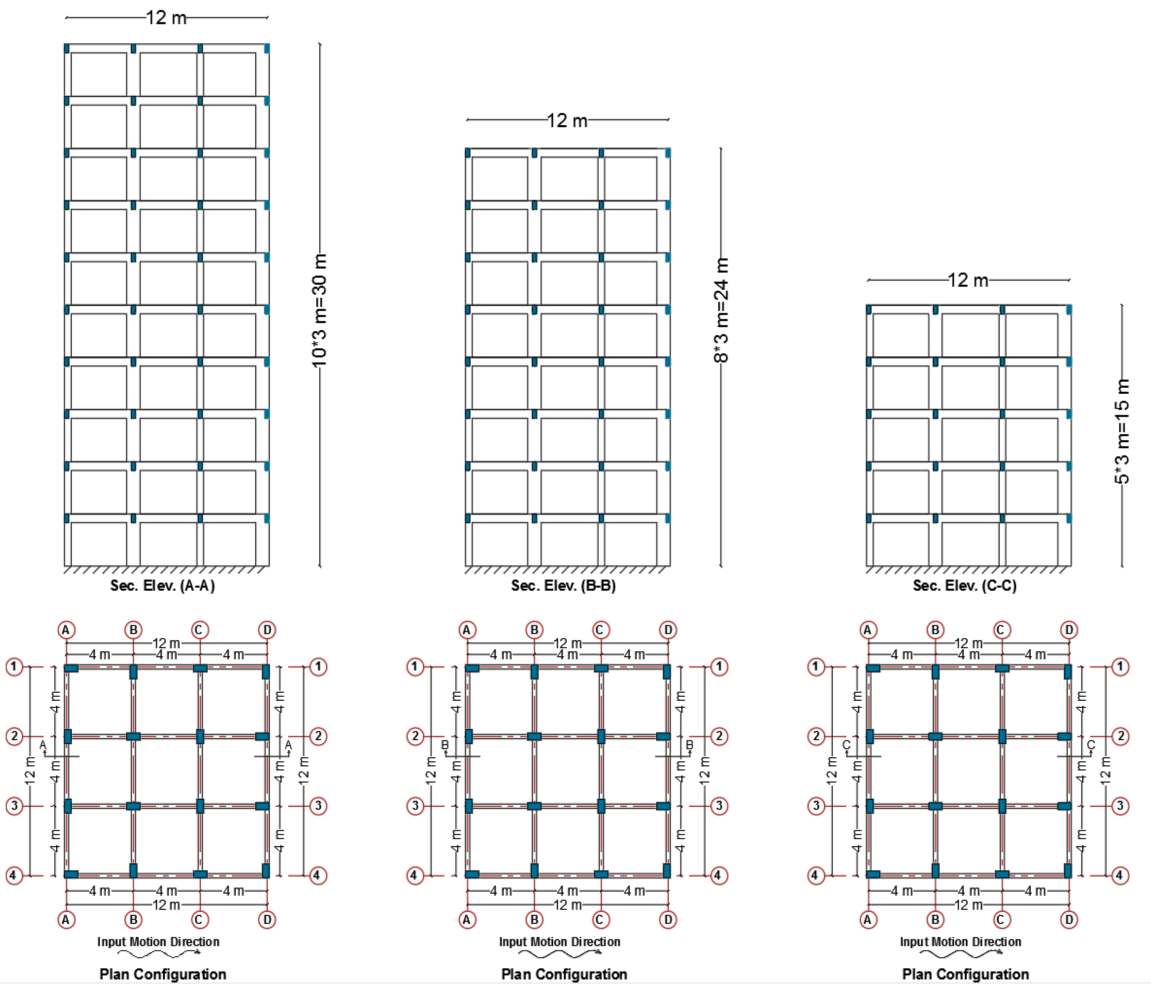


Figure (1) - ABAQUS 3D Numerical Model

Moment resisting frames are utilized to resist lateral loads acting on the considered structures. These structures are five, eight, and ten storey residential buildings with total height of fifteen, twenty-four, and thirty meters, respectively. Total width of the structure equals twelve meters consisting of three equal spans in each direction. These structures are rested on raft foundations with twelve meters in both length and width. Dimensions of the above-mentioned structures are summarized in Table 1. Plan Configurations and sectional elevations of studied structures are shown in Figure (2).

Table 1- Dimensions of Studied Structures

No. of Storeys	Storey Height (m)	Total Height (m)	No. of Bays	Bay Width (m)	Total Width (m)
5	3	15	3	4	12
8	3	24	3	4	12
10	3	30	3	4	12



a) Ten Storey Building b) Eight Storey Building c) Five Storey Building

Figure (2) – Dimensions of the Adopted Structures in the Study

5.1 Structural Elements

In ABAQUS software, beams and columns were represented by frame elements "B31", while slabs, and raft foundation were represented by shell elements "S4". Sectional properties of structural elements are summarized in Table 2. Cracked sections for the reinforced concrete elements are taken into consideration by multiplying moment of inertia of the uncracked sections (Ig) by the cracked section coefficients (0.25 for slabs, 0.50 for beams, and 0.70 for columns).

5.2 Soil Properties

In the current study, Mohr–Coulomb model has been adopted as the constitutive model to simulate nonlinear behavior of the soil medium. Mohr-Coulomb model has been adopted in various studies to simulate nonlinear behavior of soils with values of cohesion [5, 11-14] in soil-structure interaction problems. Although other advanced soil plasticity models are available but the application of such models may create complexity in dynamic analysis. Therefore, the Mohr-Coulomb model is employed in this study to achieve a balance between the analysis accuracy, and cost [14].

Mohr–Coulomb model is an elastic-perfectly plastic model. Three types of clay soils representing classes B, C, and D according to ECP-201 [15] have been used in this research to investigate the effect of soil characteristics on the seismic response of structures. The properties of these cohesive soils are summarized in Table 3. Values of Poison's ratio were taken according to the recommendation of Bowles [16] that Poisson's ratio of most clay soils ranges from 0.4 to 0.5 and the recommendation of Kulhawy et al. [17] that Poisson's ratio of partially saturated clay soils ranges from 0.3 to 0.4.

Table 2 -Sectional Properties of Structural Elements

Member Property	Five Storeys	Eight Storeys	Ten Storeys
Raft thickness (m)	0.5	0.8	1.0
Slab thickness (m)	0.12	0.12	0.12
Beam section (m^2)	0.25×0.50	0.25×0.50	0.25×0.50
Column section (m^2)	0.30×0.60	0.35×0.70 (1st-4th floors) 0.30×0.60 (5th-8th floors)	0.40×0.80 (1st-5th floors) 0.30×0.60 (6th-10th floors)

Table 3- Geotechnical Characteristics of the Investigated Soils in this Study

Soil Type	Density (t/m^3)	Cohesion (kPa)	Vs (m/s)	G_{max} (kPa)	Poisson's Ratio
B	2	330	400	320000	0.4
C	1.9	160	280	148960	0.4
D	1.8	45	150	40500	0.4

5.3 Interface Elements

Interface elements separate the contacting parts of soil and foundation. Proper modeling of the interface between soil and the foundation system is required in numerical simulation of soil-structure interaction problems. In this study, the interfaces between the foundation and soil is represented by parallel and perpendicular springs between two planes contacting each other, and the relative movement in both directions is controlled by the stiffness values of these linear springs. Normal (K_n) and shear (K_s) stiffness values of springs are set to ten times the neighboring zone stiffness as recommended by Itasca Consulting Group [18]. Stiffness values for the springs are calculated as following:

$$\boldsymbol{K_n = K_s = 10 \times max\left[\frac{(K+\frac{4}{3}G)}{\Delta Z_{min}}\right]} \tag{2}$$

Where: K & G are the bulk and shear moduli, respectively; and ΔZ_{min} is the smallest width of a neighboring zone in the normal direction as shown in Figure (3).

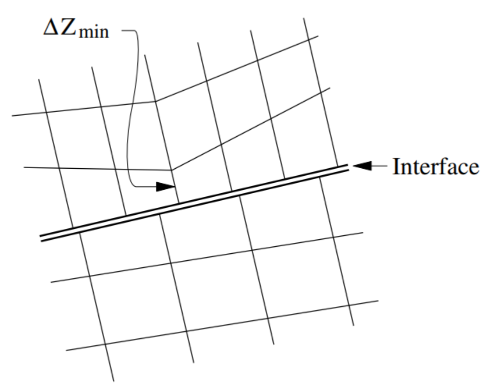


Figure (3) - Zone Dimension Used in Stiffness Calculation

5.4 Boundary Conditions

Numerical simulations are widely used to predict the seismic response of structures resting on the ground. To maintain the model size within acceptable limits, only the region of interest of the soil has to be modelled, while the rest has to be represented by artificial boundaries.

A. Lateral boundary conditions

In static problems, fixed boundary conditions can be used to represent lateral boundary conditions of soil domain. However, this assumption will not be adequate in dynamic problems as fixed boundary conditions may lead to the reflection of outward propagating waves back into the model and do not allow the necessary energy radiation, trapping energy inside the model. The simplest solution to this problem is to define a domain large enough so that waves reflected from the boundary do not have time to return to the region of interest. However, this will not be a practical solution due to the relatively high wave speeds of most soils. Therefore, it is desirable to have boundary conditions that allow the necessary energy radiation. This can be achieved using infinite elements in ABAQUS "CIN3D8", shown in Figure (4). These elements are used in problems in which the region of interest is small in size compared to the surrounding medium; they are used in conjunction with finite elements to provide "quiet" boundaries to the finite element model in dynamic analysis procedures [19].

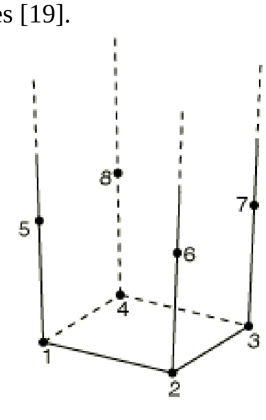


Figure (4) - Infinite Elements in ABAQUS "CIN3D8"

B. Bedrock boundary conditions

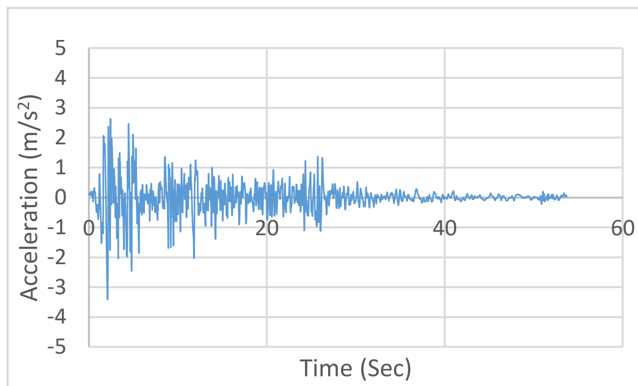
Rigid boundary condition is adopted to represent bedrock in this study. Hence, the input ground acceleration records are directly applied to the rigid base of the soil domain.

C. Distance between boundary conditions

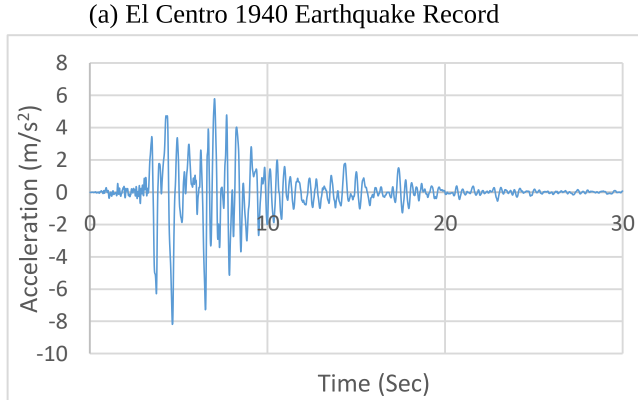
Rayhani and Naggar [11] carried out comprehensive numerical analysis and centrifuge tests and they have recommended that the horizontal distance between soil lateral boundaries should be five times the width of the structure, as the results showed that increasing that distance from five times the structure width to ten times that width has a small effect on the seismic response of the models. Also, they have recommended thirty meter as the maximum bedrock depth in the numerical analysis, which is in a good agreement with most modern seismic codes that consider the properties of the top thirty meter of the soil profile to evaluate local site effects. Hence, the horizontal distance between the soil lateral boundaries is assumed to be sixty meter (five times the structure width in this study) and the bedrock depth is assumed to be thirty meters.

6. Ground Motions

Figure (5) shows two earthquakes records, including El Centro 1940 earthquake, and Kobe, 1995 earthquake, that were adopted in this study to investigate the effects of soil structure interaction on seismic response of multi-storey buildings. Accelerograms of these earthquakes are applied at bedrock level to perform a time history analysis. Characteristics of the utilized ground motions are summarized in Table 4.



(a) El Centro 1940 Earthquake Record



(b) Kobe 1995 Earthquake Record

Figure (5) - Earthquake Records Used in the Analysis

Table 4- Earthquake Ground Motions Used in this Study

Earthquake	Country	Year	PGA (g)	M_w (R)	Duration (S)
El Centro	USA	1940	0.348	6.9	53.72
Kobe	Japan	1995	0.834	6.8	30

7. Damping

Damping can be defined as the dissipation of energy in a vibrating system. Total damping of soil structure interaction systems results from structural damping and foundation damping. Foundation damping includes combined effects of energy dissipated from waves propagating away from the system foundation (radiation damping) and hysteretic action in soil medium (material damping).

Hysteric Damping "Material Damping"

Nonlinear behavior of the soil medium can be considered using shear modulus and damping ratio as functions of induced shear strain while adopting Mohr-Coulomb failure model. Increasing soil shear strain will result in a decrease in soil shear modulus and an increase in hysteric damping ratio. The value of soil shear modulus (G) corresponding to a specific shear strain ($\boldsymbol{\gamma}$) can be calculated using the following equation:

$$\boldsymbol{G = \frac{G_{max}}{1+\frac{\gamma}{\gamma_{ref}}}} \quad (3)$$

Where γ_{ref} is the reference shear strain, $G_{max} = \rho \times Vs^2$ is the maximum shear modulus, ρ is the soil density, and Vs is the shear wave velocity in soil layer as shown in Figure (6).

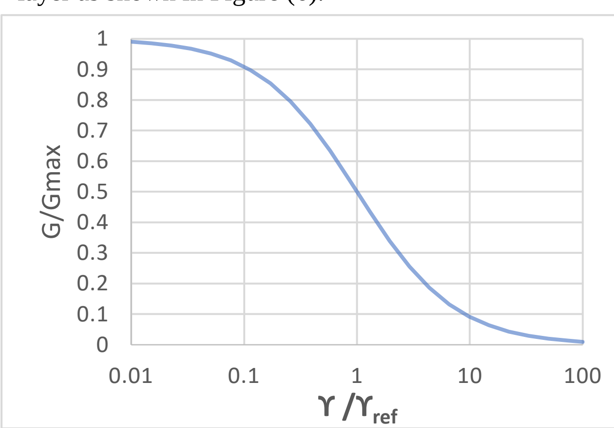


Figure (6) - Shear Modulus Degradation Curve

Hysteric damping ratio (β_S) can be calculated according to the following equation of hyperbolic model and is shown in Figure (7).

$$\beta_S = \frac{4}{\pi} \times \left[1 + \frac{1}{\frac{\gamma}{\gamma_{ref}}}\right] \times \left[1 - \frac{\ln\left(1+\frac{\gamma}{\gamma_{ref}}\right)}{\frac{\gamma}{\gamma_{ref}}}\right] - \frac{2}{\pi} \quad (4)$$

Or the equivalent equation:

$$\beta_S = \frac{4}{\pi} \times \frac{1}{1-\frac{G}{G_{max}}} \times \left[1 + \frac{\frac{G}{G_{max}}}{1-\frac{G}{G_{max}}} \times \ln\left(\frac{G}{G_{max}}\right)\right] - \frac{2}{\pi} \quad (5)$$

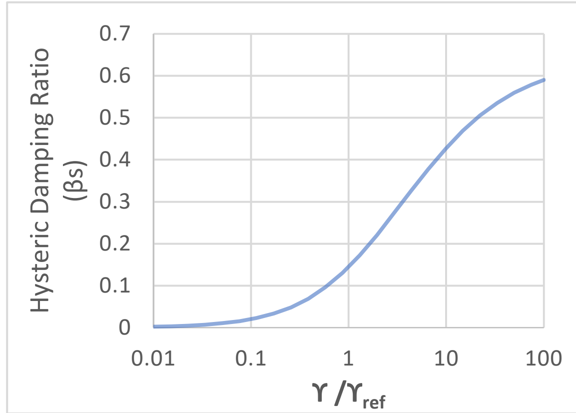


Figure (7) - Hysteric Damping Ratio and Shear Strain Curve

The values of the shear modulus and damping ratio are dependent on the shear strain induced in soil medium due to an earthquake. To get the value of this strain, an analysis of the soil under the application of the earthquake is to be performed and this analysis depends on the values of shear modulus and damping ratio. Iterative procedures are carried out to get the values of shear modulus, damping ratio and shear strain. These values of the damping ratio and shear modulus are used to simulate the real behavior of soil and to represent soil nonlinearity. Since each earthquake record induces different levels of shear strain in the soil deposit, the values for soil damping and modulus will be different for each earthquake.

7.1 Total damping

Total damping of a soil-structure system (η) comes from combined effects of structural damping and foundation damping [20] according to the following equation:

$$\eta = \frac{1}{(\tilde{T}/T)^2}\, \beta_i + \beta_f \quad (6)$$

Where:

β_i: Structural damping

β_f: Foundation damping

$\tilde{T}$: Fundamental time period of SSI system

T: Fundamental time period of fixed base system

Foundation damping can be calculated from equation (7) as a function of hysteretic damping and radiation damping.

$$\beta_f = \left[1 - \frac{1}{(\tilde{T}/T)^2}\right] \beta_s + \frac{1}{(\tilde{T}/T_x)^2} \beta_x + \frac{1}{(\tilde{T}/T_{yy})^2} \beta_{yy} \quad (7)$$

Where:

β_S: Hysteric damping

β_x: Translational damping

β_{yy}: Rotational damping

7.2 Rayleigh Damping Coefficients

Damping is defined in ABAQUS in the form of Rayleigh damping coefficients. The damping matrix in Rayleigh damping is a linear combination of mass-proportional and stiffness-proportional terms

$$[C] = \alpha[M] + \beta[K] \quad (8)$$

where $[C]$, $[M]$, and $[K]$ are the damping, mass, and stiffness matrices, respectively, α and β are Rayleigh damping coefficients used to specify the model damping ratio.

By assuming the same damping ratio (η) for two modes with natural frequencies fi and fj, or natural angular frequencies ωi and ωj, damping ratio (ξ) can be calculated using coefficients α and β as following:

$$\eta = \frac{\alpha}{2\omega_i} + \frac{\beta\omega_i}{2} \quad (9)$$

$$\eta = \frac{\alpha}{2\omega_j} + \frac{\beta\omega_j}{2} \quad (10)$$

$$\omega_i = 2\pi f_i \quad (11)$$

$$\omega_j = 2\pi f_j \quad (12)$$

And solving these equations together results in two new equations that will be used to calculate the values of α and β

$$\alpha = \eta\frac{2\omega_i\omega_j}{\omega_i+\omega_j} \quad (13)$$

$$\beta = \eta\frac{2}{\omega_i+\omega_j} \quad (14)$$

So, we need to perform a frequency analysis as an initial step for each model to determine at least two frequencies of the structure to be used in calculation of Rayleigh damping coefficients.

8. Results and Discussion

In this section, the maximum base shear force over the duration of each applied ground motion (El Centro 1940, and Kobe 1995) will be presented with different subsoil conditions. Results of 3D numerical models developed for the five, eight, and ten storey buildings are summarized and compared in the following section. Moment resisting frames were adopted as the lateral load resisting system for the analyzed models. Effects of subsoil rigidity on dynamic response of structures are discussed in terms of maximum recorded base shear forces during earthquake excitation.

Under the application of El Centro 1940 earthquake, maximum base shear force of the five storey building was recorded, and it was found to decrease with the decrease of soil rigidity as shown in Figure (8). Base shear force decreased by a ratio of 17.3% for soil B, 23.4% for soil C and 51.6% for soil D. From these results, the importance of considering SSI effects is highly clarified, especially for soil D.

For five storey buildings subjected to Kobe 1995 earthquake, higher values of base shear forces were obtained due to the higher peak ground acceleration "PGA= 0.843 g" in comparison with the El Centro earthquake "PGA=0.348 g". Base shear force decreased by a ratio of 12.8% for soil B, 13.2% for soil C, and 30.6% for soil D as shown in Figure (8).

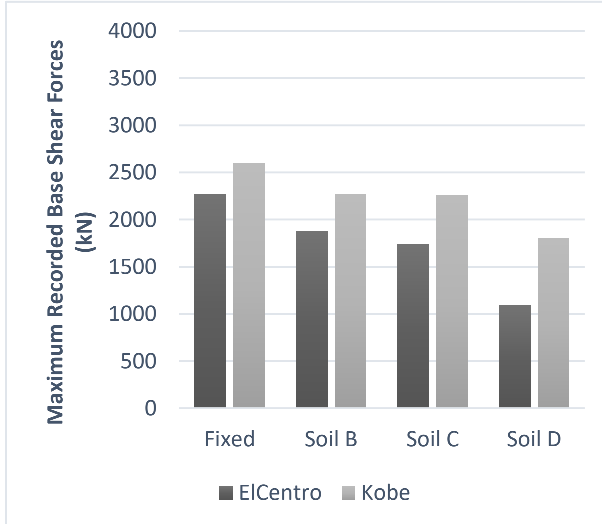


Figure (8) - Maximum Recorded Base Shear Forces (kN) of the Five Storeys Model under El Centro 1940, and Kobe 1995 Earthquakes

Figure (9) represents the values of maximum base shear forces of the eight storey buildings. Under the application of El Centro 1940 earthquake, base shear forces decreased by a ratio of 31.3%, 42.0% and 57.3% for soil B, soil C and soil D respectively. It can be stated clearly that the subsoil flexibility has markedly affected the base shear force, as these forces decreased with the decrease of the soil stiffness to reach a value less than its half in case of soil D.

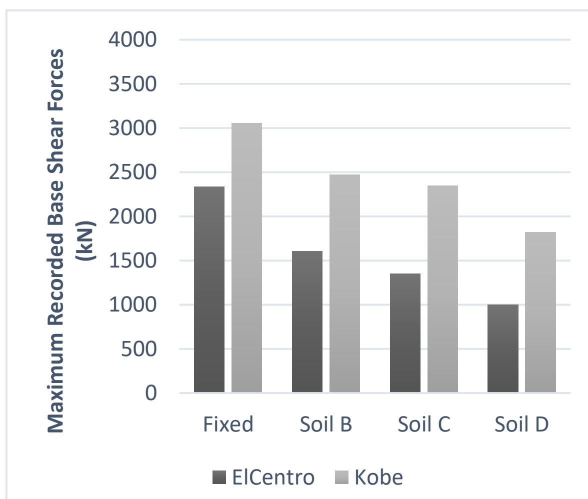


Figure (9) - Maximum Recorded Base Shear Forces (kN) of the Eight Storeys Model under El Centro 1940, and Kobe 1995 Earthquakes

For 8 storey buildings subjected to the Kobe 1995 earthquake, the reduction ratios of base shear forces of soil B, soil C, and soil D were 19.0%, 23.1%, and 40.4% respectively.

Figure (10) shows the maximum base shear forces of the ten storey buildings. Under the application of El Centro 1940 earthquake, base shear force decreased by a ratio of 29.0%, 34.4% and 56.3% for soil B, soil C, and soil D respectively. This decrease can be referred to the increase of total system damping (due to hysteric and radiation damping) and to the increase in natural period, especially for soil D.

Ten storey building models were analyzed under the application of Kobe 1995 earthquake with a peak ground acceleration "PGA" of 0.843 g. The same decrease in base shear forces in case of flexible base was found with ratios of 23.9%, 28.8%, and 56.1% for soil B, soil C and soil D, respectively.

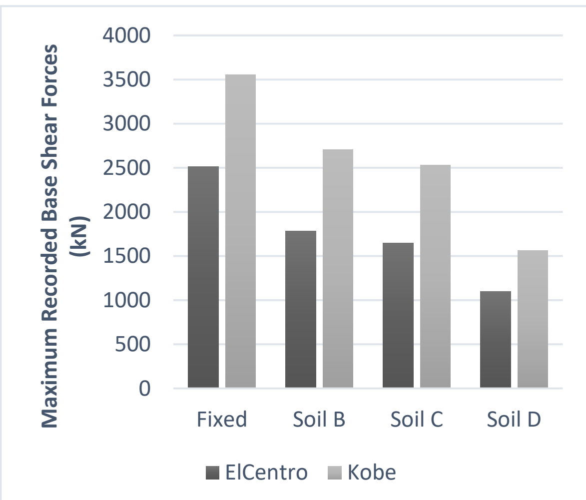


Figure (10) - Maximum Recorded Base Shear Forces (kN) of the Ten Storeys Model under El Centro 1940, and Kobe 1995 Earthquakes

9. Comparison with the Outcomes of Previously Experimental Studies

Hosseinzadeh, and Anateghi-A [21] investigated the effects of soil-structure interaction in dynamic response of multi-storey buildings. They carried out experimental tests using four building models of 5, 10, 15, and 20 storeys resting on relatively soft soil. Two real earthquake records generated by shaking table are applied to the soil-structure system. From the results, it can be concluded that considering SSI in the analysis process results in an increase in fundamental time period, and damping of the system.

Lu et al. [22] discussed the reliance on finite element method in the analysis of SSI problems by comparing the numerical model results with the results of shaking table experiments, and they concluded that finite element models can be used appropriately for the analysis of SSI phenomenon. Results of shaking table experiments showed that the natural frequency of the flexible-base system "considering SSI" is less than that of the fixed-base system, and the damping ratio of the SSI system is greater than that of the fixed-base system. Moreover, soft soil was found to filter most of the high-frequency components of the vibration wave, leaving behind the low-frequency components that results in minimizing the peak value of the acceleration under each of the applied excitations.

Vivek and Raychowdhury [23] discussed the effects of SSI on the seismic response of moment resisting frames supported by shallow footings. Shaking table tests were performed on models of 3-storey and 6-storey buildings. The models were placed in a laminar soil container and subjected to a number of earthquake excitations, and they were also tested under the fixed base conditions in order to isolate the effect of soil-structure interaction. Results showed a reduction in base moments up to 65% and 90% due to SSI effect for the 3-storey and 6-storey structure, respectively. Significant energy dissipations were found up to about 36% and 42.6% for the 3-storey and 6-storey structure, respectively.

The results of this study are in a good agreement with the outcomes of previously experimental studies, as the time period, and damping ratio were greater for flexible-base condition than fixed-base condition for all studied cases. Also, base shear forces decreased in case of considering SSI effects "flexible-base condition".

10. Conclusions

Considering the effects of soil structure interaction in dynamic analysis of moment resisting frames has become a critical issue to ensure economical and safe design. Base shear forces of the studied cases generally decrease with the increase of soil flexibility due to the increase in natural period of structures and the added damping to the system (radiation and hysteric damping). It was observed that base shear forces of the Kobe earthquake were larger than those of the El Centro earthquake for all studied cases of both fixed and flexible bases due to higher peak ground acceleration "PGA" of the Kobe earthquake. Also, percentages of decrease in base shear forces for the three types of soil were larger in case of El Centro earthquake compared to the Kobe earthquake. Finally, it can be concluded that a combined soil-structure analysis would be recommended as long as possible for the design process of multi-storey buildings as the soil structure interaction phenomenon was proved to highly influence the seismic response of these buildings.

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