Effect of Raft and Column Sizes on the Seismic Soil Structure Interaction Performance of Fifteen Storey Midrise Frame Structures

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Abstract. Seismic design of structures is usually executed by performing 1D free-field soil response analysis using design spectral acceleration charts given by codes. This method ignores soil structure interaction effects thus affecting structure-foundation-soil system behavior leading to imprecise design. Soil structure interaction refers to the dynamic behavior between the structure, underlying foundation and soil block. To understand the behavior of a 15 storey midrise concrete seismic frame structure rested on raft foundation and founded on silty sandy soil block, 3D nonlinear time history finite element simulations using Abaqus were performed. The effects of raft and column sizes were considered by modeling flexible and fixed based structures. All cases were hit at the bottom by El-Centro (1940) and Northridge (1994) earthquakes. The results were presented in terms of storey lateral deflection, inter-storey drift, shear force, foundation rocking and response spectrum. The results showed that the combination between the structure-foundation-soil natural frequencies along with the soil type used dictate the behavior of the midrise structure as well as SSI effects under the different raft and column sizes used. Therefore, a detailed study considering all above parameters must be performed by engineers to ensure safe and cost-effective designs.

Notation List: $c=$ soil apparent cohesion value[kPa], $\gamma_d=$dry unit weight[kN/m$^3$], $\rho =$density[kg/m$^3$], $\Phi=$ internal friction angle[$^\circ$], $\Psi=$dilation angle[$^\circ$], $E=$Young Modulus[MPa], $G=$ shear modulus[MPa], $f'_c=$concrete compressive strength[MPa] , $e=$void ratio, $\nu=$poisson's ratio, $PI=$plasticity index[%], $V_s=$shear wave velocity[m/s], $\gamma_c=$ cyclic shear strain[()], $A=$acceleration[g], $PGA=$peak ground acceleration[g], $S_a=$spectral acceleration[g], $\zeta=$damping ratio[)], $d_i=$ deflections at i level[mm], $h=$the story height[m], $\alpha=$mass damping factor, $\beta=$stiffness damping factor.

1. Introduction

Scientists and engineers use "seismic hazard" and "seismic risk" terms to describe earthquakes and their effects on structures, soils and lives. "Seismic hazard" describes the natural phenomena left by an earthquake such as ground shaking, fault rupture and structural hazards though "seismic risk" describes the damage to lives and structures due to a seismic hazard. Thus, depending on the vulnerability of a structure to mitigate the effects of an earthquake, a seismic hazard can either increase or decrease a seismic risk. Earthquake geo-hazard to ground shaking can be expressed in terms of ground response, site...
effects, settlements, etc. Noting that although seismic waves travel in rock over their most trips to the earth's surface, the final portion of their trip is very important. The seismic waves finish their trip by propagating through soil deposits. Therefore, depending on the characteristics of these soil deposits, the waves can be either get amplified (mainly in cohesive soils) or attenuated (mainly in cohesionless soils) [1]. Thus, the seismic response of a structure is affected by the dynamic response of the soil medium where the structure and the foundation are founded called soil structure interaction (SSI). Codes recommend designing structures base on 1D spectral acceleration neglecting SSI effects as a mean to improve the factor of safety. However, neglecting SSI in structures' design lead to a decrease in structure's fundamental period, damping ratio and lateral displacement with an increase or a decrease in structure's base shear depending on the soil spectral acceleration.

The effects of earthquakes on soils and structures have been studied by several researchers since early 1960s. Nevertheless, it wasn’t till after 1971 Mw=6.6 San Fernando earthquake that building codes started considering local site effects and research in this field expanded using analytical, experimental and numerical solutions [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. Since then, several significant earthquakes occurred around the world and expanded researchers' knowledge in this area such as 1994 Mw=6.7 Northridge and 1995 Mw=7.5 Kobe earthquakes. These earthquakes left thousands of people dead and destroyed hundred thousand of buildings leaving thousands of people homeless.

The finite element software SAP, Etabs, Ansys, Abaqus, etc and finite difference software like Flac are being used to model SSI problem using the direct method of analysis. Ref. [6], Ref. [9], Ref. [12] and Ref. [15] are among many others who showed that due to SSI effects, lateral displacement and thus inter-storey drifts of flexible-structures are greater than those of fixed-based structures. The effect of foundation type was studied by Ref. [16], Ref. [17], Ref. [9] and Ref. [10], etc. Ref. [16] and Ref. [17] found that earthquake type (near or far-field) affects soil amplification within the same soil type. Moreover, they showed that earthquake motion characteristics are affected by the structure as well as by the foundation type. Nevertheless, SSI effects can be neglected in designs when soils have shear wave velocities below 600m/s [5, 19] and in cohesionless not cohesive soils [14, 20]. In addition, Ref. [9] demonstrated that as the raft foundation size decreased, the inertial forces in the structure decreased thus, the spectral acceleration reduced significantly due to the increase in structure natural frequency leading to an increase in lateral deflection and foundation rocking.

All above researches were conducted on soft soils. This paper deals with the dynamic behavior of 15 storey concrete frame structure founded on raft foundation and silty sandy soil and analyses the effects of raft and column sizes including soil structure interaction effects. Fully 3D nonlinear seismic finite element simulations under the influence of two strong ground motions: El-Centro (1940) and Northridge (1994) were conducted using Abaqus. The results were presented in terms of storey lateral displacement, inter-storey drifts, shear force, foundation rocking and response spectrum and were used to compare the behavior of flexible to fixed-based structures. This paper highlights the importance of considering soil structure interaction effects and the influence of raft and column sizes on structures' design in terms of safety as well as cost-effectiveness.

2. Finite element model

To understand the behavior of 15 storey midrise concrete seismic frame structures rested on raft foundation and silty sandy soil, the effects of raft and column sizes were investigated by performing three-dimensional nonlinear finite element simulations using the commercial software Abaqus [21]. Flexible (S-N-C models with N referring to the raft size used and C to the column size used in each case) and fixed base structures (S-C models) were modeled by the direct method of analysis where the entire structure-raft-soil system was simulated at the same time as shown in Figure 1. Moreover, each modeled case was hit at the bottom by El-Centro (1940) Mw=6.9, PGA=0.318g near field and Northridge (1994) Mw=6.7, PGA=0.843g far field earthquakes as presented in Figure 2. The modeled configuration details and material properties used in this paper are presented in Table 1 and 2. The structure’s beams and columns were modeled using two-node linear beam B31 with 9400 elements while the structure’s slabs were modeled using four-node double curved shell S4 with 100 elements. The raft and soil block were modeled using eight-node linear brick, reduced integration, hourglass control continuum solid elements C3D8R: the raft with around 4800 elements and the soil block with 96500 elements. Moreover, uniformly
distributed live and dead load of 2.5 kN/m² was applied to the structures’ floors. The bottom soil boundary was assumed fixed while the horizontal soil boundaries were modeled as quiet boundary conditions using one-way infinite brick elements CIN3D8 to simulate the absorbed energy from the unbounded soil domain. Element interactions were accounted for by tying structures’ beams and slabs as well as columns and raft and raft and soil surfaces whereas embedded columns were placed in flexible models’ rafts. Noting that each modeled case took around 60 hours to be completed using fast computational facilities at Université Saint-Joseph de Beyrouth.

Structural elements were modeled using elastic-perfectly plastic material while considering 5% Rayleigh material damping. Then, the mass damping factor (α) and the stiffness damping factor (β) were calculated based on first and second mode structural frequencies (fᵢ and fⱼ in rad/s) obtained using linear perturbation procedure and Lancoz method available in Abaqus (Table 3):

\[
\zeta = \frac{1}{2 f_n} \alpha + \frac{f_n}{2} \beta 
\]

(1)

\[
\alpha = 2 \zeta_i f_i f_j / f_i + f_j 
\]

(2)

\[
\beta = 2 \zeta_i f_i f_j / f_i + f_j 
\]

(3)

Moreover, dense silty sandy soil having a shear wave velocity of 63 m/s was used in this paper. To calculate its shear modulus (G) and damping ratio (ζ), equivalent linear method was used. In this method, the maximum cyclic shear strain for each soil element was determined by performing linear analysis of preliminary assumed values of G and ζ [22,23,24]. Then, using backbone curves given by Ref. [25] that relates G and ζ to the cyclic shear strain for different plasticity indices for cohesive soils, new values of G and ζ were obtained. These values were therefore applied in the numerical model and this phase was repeated until no further change in G and ζ were

| Table 1. Model configuration |
|-----------------------------|
| Number of Bays | Storey Height [m] | Bay Width [m] | Column [cm] | Beam [cm] | Slab [m] |
|----------------|-------------------|--------------|-------------|-----------|---------|
| 3              | 3                 | 5            | 50X50, 50X100 | 50X50    | 5X5X0.25 |

Soil Dimensions

| Height [m] | Length [m] | Width [m] | Raft Dimension |
|------------|------------|-----------|----------------|
| 30         | 150        | 150       | 20(1.3B), 22.5(1.5B), 30(2B) |

| Average PGA = 0.318g |
|----------------------|
| El-Centro (1940)     |
| Near-field Earthquake |
| Mw = 6.9(R)         |

| Average PGA = 0.843g |
|----------------------|
| Northridge (1994)    |
| Far-field Earthquake |
| Mw = 6.7(R)         |
obtained. Using initial linear perturbation procedure and Lancoz method available in Abaqus, first and second mode soil frequencies were determined to calculate soil Rayleigh damping coefficients (Table 3). Noting that each earthquake is unique, thus each earthquake possesses its own damping coefficients.

| Table 2. Material Properties |
|-----------------------------|
| Concrete                    |
| E [GPa] 14                  |
| ν 0.2                         |
| ρ [kg/m³] 2400               |
| f' [MPa] 20                  |
| Silty Sandy Soil             |
| γmax [%]*                   |
| G/G_max*                    |
| ζ [%]*                      |
| α & β*                      |
| El-Centro (1940)            |
| 1.72                        |
| 0.085                       |
| 20.5                        |
| 0.63, 0.066                 |
| Northridge (1994)           |
| 1.82                        |
| 0.0769                      |
| 21                          |
| 0.65, 0.068                 |
| E [MPa] 20                  |
| ν 0.3                        |
| γd[kN/m³] 18.98             |
| e 0.4                       |
| φ° 35                        |
| ψ° 10                       |
| c [kPa] 50                  |
| V_s[m/s²] 63                |
| PI [%] 15                   |

| Table 3. Structures’ natural frequencies |
|------------------------------------------|
| Reference name | f1[Hz] | f2[Hz] | α* | β* |
|----------------|-------|-------|----|----|
| S15-C-0.5-0.5m | 0.47  | 1.45  | 0.2 | 0.00
|                |       |       | 2  | 8  |
| S15-C-0.5-1m   | 0.54  | 1.64  | 0.2 | 0.00
|                |       |       | 5  | 7  |

* after [25]

3. Results and analysis

To study the effects of raft and column sizes of a 15 storey seismic concrete frame structure, the size of the raft foundation was varied between 1.3, 1.5 and 2B with B=15m being the width of the structure under 2 different column sizes: 50 X 50 cm and 50 X 100 cm with 100 cm being in the direction of the earthquake load. All raft foundations had thicknesses of 1.5m and the soil boundary limits were chosen after a series of parametric simulations and the recommendations of Ref. [26], Ref. [27] and Ref. [28]. The results, presented in Figures 3 to 5 and Tables 4 in terms of storey lateral deflection, inter-storey drifts, shear force, foundation rocking and response spectrum, compare the results of flexible to fixed base cases. Noting that all cases were hit at the bottom by El-Centro (1940) and Northridge (1994) earthquakes. In addition, storey lateral deflection plots, plotted when the maximum lateral deflection occurs at top of the structure regardless what time it occurred [28, 29], were measured relative to the base of the structures.

3.1 Lateral deflection and Inter-storey drifts

The results presented in Figures 3 and 4 show that flexible structures present higher lateral deflections than fixed base structures showing SSI effects which is accordance with Ref. [6], Ref. [9], Ref. [12] and Ref. [15]. Moreover, 1.5 and 2B raft sizes present similar deflection curves under both earthquakes. Also, increasing the raft size from 1.3 to 2B for C-0.5-0.5m cases increased top storey lateral deflection by a ratio of 1.41 and 1.12 under El-Centro (1940) and Northridge (1994) earthquakes respectively. However, increasing the raft size from 1.3 to 2B for C-0.5-1m cases decreased top storey lateral deflection by a ratio of 0.56 and 0.86 under El-Centro (1940) and Northridge (1994) earthquakes respectively.

Therefore, lateral deflection increased for 1.3B cases while it decreased for 2B cases when increasing the column sizes under both excitations. For example, lateral deflection at top of the structure decreased by a ratio of 0.69 from S15 C-0.5-0.5m to C-0.5-1m while it increased by a ratio of 1.24 from S15-1.3B C-0.5-0.5m to C-0.5-1m and then decreased by a ratio of 0.49 from S15-2B C-0.5-0.5m to C-0.5-1m.
These lateral deflections are used to calculate the level of damage of a structure from a seismic excitation. This damage parameter called inter-storey drift is calculated as the difference between the lateral deflection of two stories divided by the storey height:

\[
drift = \left( d_i - d_{i+1} \right) / h
\]

It is divided into 5 categories: if inter-storey drift < 0.2%: fully operational, < 0.5%: operational, < 1.5%: life safe, < 2.5%: near collapse and > 2.5%: collapse with life safe category being the acceptable limit by most seismic codes [30, 31]. As shown in Figure 3 and 4, increasing raft size pushed inter-storey drift curves into higher categories where it reached collapse under Northridge (1994) earthquake. Therefore, even though both earthquakes had similar magnitudes, the increase in raft size was more pronounced under El-Centro (1940) earthquake while the safety of the structure was more affected under Northridge (1994) earthquake having higher PGA value.

Soil structure interactions are divided into kinematic and inertial interactions. Kinematic interactions are caused by the stiffness of the structure while inertial interactions are caused by the mass of the structure and the foundation. Thus, increasing the size of the raft or the column increases the mass of the structure-foundation...
system ending in extra inertial interaction manifested by the increase in the system’s base motion. However, this motion is related to the ability of the system to match kinematic interaction [1] and depending on the soil stiffness, kinematic interaction can cause a decrease in structure’s base motion [18]. In general, increasing raft size tends to decrease structure’s lateral deflection. Nevertheless, due to the use of silty sandy soil, the combination between the structure-foundation-soil different natural frequencies as well as wave attenuation, earthquake PGA and column stiffness caused larger foundations to attract more energy than smaller foundations under C-0.5-0.5m cases. In other words, SSI effects were more pronounced at larger foundation structures under C-0.5-0.5m cases and the opposite under C-0.5-1m cases. The results presented in this paper are not entirely in parallel with Ref [9] who due to his use of clayey soil, seismic wave was amplified when it reached top of the soil profile and led to the decrease in lateral deflection and inter-storey drift values.

3.2 Foundation Rocking
Lateral deflections and inter-storey drifts values depend on the amount of structural rocking component experienced by the structure. They are caused by the inertial forces formed in the structure that cause compression on the first side of the foundation along with a possible uplift on the other side. As shown in Table 4, the increase in raft size caused a decrease in foundation rocking under both column sizes like the results obtained by [9]. The foundation rocking angle decreased from 0.22° to 0.08° when increasing the raft size from 1.3 to 2B for C-0.5-0.5m under El-Centro (1940) ground motion. Nevertheless, using Ref [32] and Ref [33] relationship that relates the foundation rocking angle to the amount of structure’s distortion and rocking components, the results showed that the increase in raft size caused a decrease in the amount of distortion component with an increase in the amount of rocking component. For example, taking C-0.5-1m under Northridge (1994) excitation case, the maximum lateral displacement of S15 was equal to 687.8mm corresponding to the distortion component. This lateral displacement increased in S15-1.3B to 1125.38mm with a rocking angle of 0.78° thus dividing it into 877.80mm as distortion component (78%) and 247.58mm (22%) as rocking component. Then, it decreased in S15-2B to 1084.31mm with a rocking angle of 0.27° thus dividing this latter into 292.76mm as distortion component (27%) and 791.55mm (73%) as rocking component.

On the other hand, the results showed that the increase in column stiffness (its size) caused an increase in structure’s distortion component and a decrease in its rocking component. Taking S15-2B Northridge (1994) earthquake case as an example, the maximum lateral displacement of S15 C-0.5-0.5m was equal to 643.56mm (distortion component), it increased in S15-2B to 1159.6mm: 197.13mm (17% distortion component) and 962.5mm (83% rocking component). While the maximum lateral displacement of S15 C-0.5-1m was equal to 687.8mm (distortion component), it increased in S15-2B to 1084.31mm: 292.76 (27% distortion component) and 791.55mm (73% rocking component). Noting that for the same column-raft size case, foundation rocking angle was greater under Northridge (1994) than under El-Centro (1940) earthquake since Northridge (1994) possesses a higher PGA causing a larger earthquake wave beneath the system. Thus, the relative structural displacement, divided into structural and rocking components, is related to SSI effects expressed by the interaction between the column stiffness, raft size, soil type and earthquake wave.

3.3 Level shear force and response spectrum
Shear force and response spectrum plots were plotted in Figures 3 to 5 noting that to calculate the maximum absolute shear force at every storey, all shear forces produced by all columns in each storey were summed up. The results, presented in Table 5, showed that raft size slightly affected average level shear force values under both earthquakes for a given column size. However, the increase in column size decreased average level shear force value of flexible to fixed base models for a given raft size. For example, the average level shear force of flexible to fixed base models increased from 0.99 to 1.03 and from 1.20 to 1.28 from 1.3B to 2B for C-0.5-0.5m cases under El-Centro (1940) and Northridge (1994) earthquakes respectively as detailed in Table 5. The

| Reference name | El-Centro (1940) | Northridge (1994) |
|----------------|------------------|-------------------|
| C-0.5X0.5m     |                  |                   |
| S15-1.3B       | 0.22             | 0.44              |
| S15-1.5B       | 0.15             | 0.31              |
| S15-2B         | 0.08             | 0.17              |
| S15-1.3B       | 0.23             | 0.78              |
| C-1X0.5m       |                  |                   |
| S15-1.5B       | 0.13             | 0.58              |
| S15-2B         | 0.07             | 0.27              |
increase in column size increased structure’s natural frequency (Table 1) resulting in more SSI effects pronounced by lower average level shear force values [34].

Using a Fortran code, the variation of pseudo-acceleration response spectrum plots (Sa) with different natural periods at 5% damping of horizontal accelerations formed at structures’ base, at top of the soil profile (Free Field: FF) and of the input earthquake were created (Figure 5). Also, using MATLAB [35], Fourier transformation of the strong ground motions produced at top of the soil surface (FF) and at the base of the structure-foundation system were generated also at 5% damping (not shown due to page size limits). The plots showed that due to the use of silty sandy soil, which is a combination of cohesive and cohesionless soil, input earthquake wave was attenuated when it reached top of the soil profile (FF). Noting that a small wave amplification happened between FF and structures’ base illustrating SSI effects which is in parallel with [27]. Also, increasing raft and column size slightly affected response spectrum curves like the results obtained by [9] who obtained a negligible response spectrum variation when increasing the raft size from 1.1 to 2B.

Table 5. Average level shear force of flexible to fixed base models

| Column size | C-0.5X0.5m | C-0.5X1m |
|-------------|------------|----------|
| Model S15-  | 1.3B 1.5B 2B | 1.3B 1.5B 2B |
| El-Centro (1940) | 1.20 1.27 1.28 | 0.96 0.96 0.96 |
| Northridge (1994) | 0.99 1.01 1.03 | 0.80 0.92 0.98 |

Figure 5. Acceleration response spectrum with 5% damping ratio for the midrise frame structure under the influence of a) El-Centro (1940) and b) Northridge (1994) earthquakes

4. Conclusions
The behavior of 15 storey seismic midrise concrete frame structure rested on raft foundation and founded on silty sandy soil under the effects of raft and column sizes while considering SSI effects was investigated in this paper. The results showed that the size of raft as well as column stiffness can affect the performance of the structure. Larger foundations can attract more energy than smaller foundations. However, the increase in raft size and the decrease in column size cause a decrease in the amount of distortion component with an increase in the amount of rocking component. Nevertheless, raft size slightly affects shear force values and response spectrum curves while the increase in column size decreases average level shear force values. These results were related to the use of silty sandy soil as well as the relation between the structure-foundation-soil different natural frequencies, earthquake wave attenuation and PGA along with column stiffness and raft size. Thus, engineers should carefully consider all above parameters in design to ensure safety and cost effectiveness.

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