Effect of Number of Stories on the Seismic Soil Structure Interaction Performance of Midrise Frame Structures

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Abstract. When an earthquake hits, a state of emergency is declared that shakes lives and infrastructures and provokes aftershocks including fires and medical emergencies. The response of midrise concrete frame structures to a seismic excitation is related to the dynamic interaction between the structure, foundation and soil called soil structure interaction (SSI). To study the effect of structures’ number of stories on the seismic behavior of midrise concrete frame buildings including soil structure interaction effects, 5 to 15 stories structures were simulated by performing 3D time history nonlinear finite element simulations using Abaqus under the influence of El-Centro (1940) and Northridge (1994) earthquakes. The models consisted of frame structures supported by raft foundation and rested on silty sandy soil block. The results presented in terms of story lateral deflection, inter-storey drift, shear force, foundation rocking and response spectrum show that structures’ number of stories significantly affect SSI effects and increasing story number can end in structures’ collapse in some cases.

Notation List: c= soil apparent cohesion value [kPa], γ = dry unit weight [kN/m³], ρ = density [kg/m³], Φ = internal friction angle [°], Ψ = dilation angle [°], E = Young Modulus [MPa], G = shear modulus [MPa], f’c = concrete compressive strength [MPa], e = void ratio, ν = poisson’s ratio, PI = plasticity index [%], Vs = shear wave velocity [m/s], Yc = cyclic shear strain [%], a = acceleration [g], PGA = peak ground acceleration [g], Sa = spectral acceleration [g], ζ = damping ratio [%], di = deflections at i level [mm], h = the story height [m], α = mass damping factor, β = stiffness damping factor.

1. Introduction
When a 6.7 earthquake hit Northridge neighborhood in Los Angeles in 1994, at least 57 people died and $25 billion in damage were caused. This kind of strong earthquakes shook residents’ lives and affected infrastructures forcing cities to declare states of emergencies. The response of midrise concrete frame structures founded on soft soils to strong shakings depends on the response of the soil medium beneath it having its own characteristics. Soil structure interaction (SSI) is the dynamic interaction problem between the structure, foundation and underlying soil or rock. SSI can either amplify or attenuate a seismic response depending on the soil response spectrum [1].

To improve the factor of safety, most seismic codes neglect the effects of SSI for structures founded on soft soils. This is due to the fact that SSI tend to increase structure’s fundamental period, damping ratio and lateral displacement while they tend to increase or decrease structure’s base shear depending on the
soil spectral acceleration. Since 1970s, researchers have studied the effects of SSI on structures using analytical, experimental and numerical solutions [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, etc]. For the past 20 years, numerical solutions using 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. [5] and Ref. [17] showed that SSI effects can only be neglected in soils having shear wave velocities below 600m/s. Moreover, Ref. [14] and Ref. [18] demonstrated that SSI effects can be neglected in cohesionless not cohesive soils. On the other hand, Ref. [6], Ref. [9], Ref. [12] and Ref. [15] showed that due to SSI effects, lateral displacement and thus inter-storey drifts of flexible-structures are greater than those of fixed-based structures. While Ref. [12] proved that SSI effects get amplified with story height.

All these researches were performed on clayey soil (cohesive soils). Therefore, 3D nonlinear finite element simulations using Abaqus [19] were performed in this article to investigate the effect of number of stories on the seismic soil structure interaction performance of midrise concrete frame structures supported by raft foundation and rested on silty sandy soil under the influence of two strong ground motions: El-Centro (1940) and Northridge (1994). The results of flexible and fixed structures were in terms of story lateral displacement, inter-storey drifts, shear force, foundation rocking and response spectrum. The main objective of this paper is to understand the behavior of midrise concrete frame structures rested on silty sandy soil therefore, aid engineers in structures’ design.

2. Finite element model

Buildings can be divided into low, medium and high rise depending on the number of stories (N): if N≤5: low-rise buildings, if 5≤N≤15: medium-rise buildings and if N≥15: high-rise buildings. The finite element software Abaqus 2017 [19] was used to study the effect of number of stories on the seismic performance of midrise concrete structures including soil structure interaction effects by varying N between 5 and 15. The results of the flexible models consisting of the structure, raft and soil block (SN-e-models with e referring to the raft thickness used in each case) were compared to the results of the fixed models consisting of the structure alone (SN-models) (Figure 1). All models were simulated using the direct method of analysis: the entire structure-raft-soil system was simulated at the same time and each model was rested on 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. Noting that every time history model took around 60 hours to be completed using fast computational facilities at Université Saint-Joseph de Beyrouth.

Table 1 presents the model configuration details while Table 2 presents the properties of the materials used in this paper. The beams and columns were modeled using two-node linear beam B31 with 9400 elements while the slab was modeled using four-node double curved shell S4 with 100 elements. Moreover, 2.5 kN/m² uniformly distributed live and dead load was applied to the structures’ floors. All frames were supported on a 20m width solid raft foundation modeled using eight-node linear brick, reduced-integration, hourglass control continuum solid elements C3D8R with 4800 elements. The structureoundation system was then rested on a dense silty sandy soil solid block modeled also using C3D8R but with 96500 elements. While one-way infinite brick elements C13D8 elements were used to account for the absorbed energy from the unbounded soil domain in the horizontal directions. The beams and floor slabs were tied in the frame structure and a special tie procedure was performed between the columns and raft as well as between the raft and soil. In addition, embedded columns were inserted in the raft in flexible models.

Table 3 presents structures’ natural frequencies calculated via linear perturbation procedure and Lanczos method available in Abaqus. Thus, the inelastic behavior of structural elements was modeled using elastic-perfectly plastic material while considering Rayleigh damping. 5% structural damping (ζ) was used to calculate the mass damping factor (α) and the stiffness damping factor (β) based on first and second mode frequencies (f₁ and f₂) in rad/s as detailed in Table 3 where [20]:

\[ \zeta = \frac{1}{2f_n} \alpha + \frac{f_n}{2} \beta \]  \hspace{1cm} (1), \quad \alpha = 2\zeta, \quad f_i f_j \]  \hspace{1cm} (2) and \quad \beta = 2\zeta, \quad \frac{1}{f_i + f_j} \]  \hspace{1cm} (3)

Moreover, the equivalent linear method was used to calculate the shear modulus (G) and damping ratio (ζ) of the silty sandy soil having a shear wave velocity of 63m/s [21,22,23]. A linear analysis using preliminary assumed values of G and ζ was performed. Then, the maximum cyclic shear strain recorded
for each element in the soil model was implemented in the backbone curves given by Ref. [23] that relates $G$ and $\zeta$ to the cyclic shear strain for different plasticity indices for cohesive soils. Therefore, the new $G$ and $\zeta$ values obtained from these curves were implemented in the numerical model. This stage was repeated until no further change in $G$ and $\zeta$ were obtained. Then, using first and second mode soil frequencies obtained also using Abaqus, Rayleigh damping coefficients were calculated for each earthquake as detailed in Table 2.

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**Figure 1.** Geometry and model mesh distribution

**Figure 2.** Acceleration with respect to time of a) El-Centro (1940) and b) Northridge (1994) earthquake

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**Table 1.** Model configuration

| Number of Bays | Story Height [m] | Bay Width [m] | Column [cm] | Beam [cm] | Slab [m] |
|----------------|------------------|---------------|-------------|-----------|---------|
| 3              | 3                | 5             | 50X50       | 50X50     | 5X5X0.25|
| Soil Dimensions|                  |               |             | Raft Dimension |
|                | Height [m] | Length [m] | Width [m] | Length [m] | Width [m] | Thickness [m] |
| 30             | 150          | 150          | 20        | 20        | 0.5, 0, 7, 1, 2.1, 1.5 |

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**Table 2.** Material Properties

| Concrete      | $E$ [GPa] | $\nu$ | $\rho$ [kg/m$^3$] | $f'_c$ [MPa] |
|---------------|-----------|-------|-------------------|---------------|
|               | 14        | 0.2   | 2400              | 20            |
| Silty Sandy Soil |         |       |                   |               |
| $\gamma_{max}$[%]* | G/G$\gamma_{max}$* | $\zeta$[%]* | $\alpha$ & $\beta$* |                   |
| 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] | $\nu$ | $\gamma_d$ [kN/m$^3$] | $e$ | * after [22] |
| 20 | 0.3 | 18.98 | 0.4 |              |
| $\phi^o$ | $\psi^o$ | $c$ [kPa] | $V_s$ [m/s$^2$] | $\pi$ [%] |
| 35 | 10 | 50 | 63 | 15 |
Table 3. Structures’ natural frequencies

| Reference name | f1[Hz]  | f2[Hz]  | α*  | β*  |
|----------------|---------|---------|-----|-----|
| S5             | 1.079   | 3.679   | 0.5 | 0.00|
| S7             | 1.0651  | 3.251   | 0.5 | 0.00|
| S10            | 0.6827  | 2.075   | 0.3 | 0.00|
| S12            | 0.605   | 1.842   | 0.2 | 0.00|
| S15            | 0.473   | 1.445   | 0.2 | 0.00|

* after [22]

3. Results and analysis

Previous studies compared SSI effects of flexible to fixed-based structures founded on cohesive soils [6,4,14,15,12,9,10, etc]. In this paper, the effect of number of stories on the seismic performance of midrise concrete frame structures while considering soil structure interaction effects was investigated by varying the stories between 5, 7, 10, 12 and 15 under the influence of El-Centro (1940) and Northridge (1994) earthquakes. Midrise soil structure interaction models: flexible-base models founded on 20m width raft foundation and supported by 150m X 150m wide and 30m height silty sandy soil block as shown in Figure 1 and Table 1 were simulated using the direct method of analysis. The soil boundary limits were chosen based on the recommendations of Ref. [24], Ref. [25] and Ref. [26]. Moreover, the results of flexible models, plotted in Figure 3 to 5 and presented in Table 4 and 5 in terms of story lateral deflection, inter-storey drifts, shear force, foundation rocking and response spectrum were then compared to those of fixed-base models.

3.1 Lateral deflections and inter-storey drifts

Inter-storey drift is a performance damage parameter that expresses the level of damage of a structure due to a seismic excitation. It is calculated as the difference between the lateral deflection of two stories divided by the story height:

$$\text{drift} = \frac{(d_i - d_{i+1})}{h} \quad (4)$$

Performance levels are classified into 5 categories depending on the inter-storey drift value: if inter-storey drift < 0.2%: fully operational, < 0.5%: operational, < 1.5%: life safe, < 2.5%: near collapse and > 2.5%: collapse. Noting that life safe category is the acceptable category limit by most seismic codes [27, 28]. The lateral deflection at each story, presented when the maximum lateral deflection occurred at top of the structure regardless what time it occurred based on Ref. [26] and Ref. [29] was measured relative to the structure’s base.

The results, plotted in Figures 4 and 5, showed that when structure’s number of stories is greater than 10, lateral deflection of flexible models founded on silty sandy soils is in accordance with those founded on soft soils. In other words, lateral deflection of flexible models is greater than those of fixed-based models. This is in parallel with the results presented by Ref. [6], Ref. [9], Ref. [12] and Ref. [15]. However, lateral deflections of fixed-based lower stories structures: S5 and S7 were higher than those of flexible models. The ratio of flexible to fixed S15, S10 and S5 models varied between 1.9,1.33 and 0.5 and between 1.6, 1.7 and 0.9 under El-Centro (1940) and Northridge (1994) ground motions respectively. Therefore, the increase in lateral deflection from fixed to flexible models is related to the amount of energy the raft and soil absorb caused by the changes in the dynamic characteristics of the structure-soil-foundation system under a seismic excitation.

Moreover, lateral deflection at top of the structures increases with story number. For example, lateral deflection of flexible S5 to S15 models increased by a ratio of 8 and 6.7 at top of the structures and by 3.17 and 3 at the 5th level under El-Centro (1940) and Northridge (1994) earthquakes respectively. This increase in lateral deflection led to shifts in inter-storey drifts curves to higher and more dangerous categories. S10, S12 and S15 structures shifted from life safe category under El-Centro (1940) earthquake to near collapse and collapse categories under Northridge (1994) earthquake. Therefore, lateral deflections and thus inter-storey drift results were more affected by the stronger ground motion having higher PGA even though both earthquakes had similar magnitudes.
3.2 Shear force and Response Spectrum
To reflect the amount of energy the structure absorbs during an earthquake, shear force and response spectrum plots were generated. The maximum absolute shear force at each story level was calculated by summing up all shear forces produced by all columns in a given story. 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. Also, using MATLAB [30], 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. The results, illustrated in Figure 3 and 4, show that average level shear forces of flexible to fixed-base structures of S10, S12 and S15 structures were found greater than one whereas those of lower rise structures S5 and S7 structures were found lower than one under both earthquakes unlike the results obtained by [3, 6, 14, etc]. Hence, as the number of stories increase, structures’ natural frequency tends to decrease and SSI effects get more significant. This is parallel with Ref. [31], Ref. [32] and Ref. [33] who showed that high frequencies structures are more affected by SSI effects than low frequencies structures. Response spectrum plots (Figure 5 and 6) present the seismic wave attenuation obtained from the input earthquake to the soil top surface (FF) caused by the soil type used: silty sandy soil. Noting that a wave amplification was obtained from FF to structure’s base and structure-foundation system base similar to [25].

This amplification illustrates SSI effects. For example, Sa was attenuated from 0.94g at the ground level to 0.294g at FF then it was amplified to 0.50g at S15 flexible structure’s base under El-Centro (1940) excitation. Thus, since level shear force tends to increase or decrease depending on the stiffness of the structure and the properties of the soil profile, the attenuation in the seismic waves caused lower frequencies structures to get more affected by SSI effects than higher frequencies structures.

Table 4. Average level shear ratios of flexible to fixed based cases

| Number of stories | 5    | 7    | 10   | 12   | 15   |
|-------------------|-----|-----|-----|-----|-----|
| El-Centro (1940)  | 0.4 | 0.5 | 1.0 | 1.0 | 1.2 |
|                   | 8   | 5   | 1   | 0   |     |
| Northridge (1994) | 0.6 | 0.2 | 1.1 | 0.9 | 0.9 |
|                   | 5   | 6   | 1   | 7   | 8   |
**Figure 3.** a) Lateral deflection, b) inter-storey drift and c) maximum shear force distribution of flexible and fixed-base models under El-Centro (1940) earthquake

**Figure 4.** a) Lateral deflection, b) inter-storey drift and c) maximum shear force distribution of flexible and fixed-base models under Northridge (1994) earthquake
3.3 Foundation Rocking
Relative structural displacement under a seismic excitation divided into structural and rocking components is caused by soil structure interaction effects [1]. Structural lateral deflection and inter-storey drifts depend on the amount of structural rocking experienced by a structure during a strong ground motion. Structural rocking is caused by inertial forces formed in a structural that cause compression on the first side and possible uplift on the other side of the foundation. Table 5 details the maximum foundation rocking experienced by the different simulated models. As shown in this table, the increase in structures’ number of stories amplified soil structure interaction effects that led to the augmentation in foundation rocking under both earthquakes. S5 to S15 flexible structures maximum foundation rocking increased from 0.038° to 0.22° and from 0.11° to 0.44° under El-Centro (1940) and Northridge (1994) earthquakes respectively. To determine the amount of lateral displacement due to rocking from the foundation rocking angle, Ref. [34] and Ref. [35] relationship was used. For example, for S10 flexible structures under Northridge (1994) earthquake, the maximum foundation rocking angle was equal to 0.36° therefore, 36% of the maximum lateral deflection at top of S10-e-1m structure was due to rocking component and 64% was due to distortion component. In other words, the 816mm maximum lateral deflection at top of S10-e-1m structure was divided into 294mm due to rocking component and 522mm due to distortion component while the maximum lateral deflection at top of S10 structure was equal to 491mm and was due entirely to distortion component. As a conclusion, SSI effects increase foundation rocking angle reflected in the increase in the amount of structural and distortion component in flexible-based structures compared to fixed-based structures.

| Reference name | El-Centro (1940) | Northridge (1994) |
|----------------|------------------|-------------------|
| S5-e-0.5m      | 0.04             | 0.11              |
| S7-e-0.7m      | 0.054            | 0.24              |
| S10-e-1m       | 0.11             | 0.36              |
| S12-e-1.2m     | 0.16             | 0.42              |
| S15-e-1.5m     | 0.22             | 0.44              |
4. Conclusions
The effect of number of stories on the behavior of midrise concrete seismic frame structures while including soil structure interaction effects was investigated by performing 3D nonlinear simulations using Abaqus. Fixed and flexible based structures (formed of the structure, raft and silty sandy soil block) were modeled and hit at the bottom by El-Centro (1940) and Northridge (1994) earthquakes. The results showed that low frequency structures got more affected by SSI effects than high frequency structures. This was reflected by lateral deflection, inter-storey drift, level shear force as well as response spectrum results. Moreover, the results showed that lateral deflection and thus inter-storey drift increased with structures’ number of stories and depending on the earthquake PGA, some structures cases got destructed. Moreover, foundation rocking angle increased with structures’ number of stories which was reflected by the increase in the amount of structural and distortion components in flexible-based structures compared to fixed-based structures.

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