

NUMERICAL INVESTIGATION OF SOIL PLASTICITY EFFECTS ON THE SEISMIC RESPONSE OF RC MOMENT RESISTING FRAMES

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ABSTRACT:

Soil-Structure Interaction (SSI) represents an interdisciplinary issue characterized by complex material and geometrical nonlinearities affecting mutually the supporting soil and the superstructure of the system during a seismic event that can compromise serviceability. In this study the following objectives are developed: i) to evaluate the effects of the inelastic supporting soil behavior on the interaction of soil-structure systems; ii) to investigate the changes in the dynamic behavior of archetype low and mid-rise moment resisting building frames when inelastic soil deformation develops. To reach these goals, numerical models of linear-elastic and nonlinear-inelastic underlain soil of buildings on shallow foundations are subjected to earthquake time histories with different frequency content. By employing the finite difference software FLAC2D, the direct method which is capable to tackle SSI issues is used to accounting for soil nonlinearities. A succession of parametric analyses is performed. The slenderness of the superstructure as well as the frequency content of input excitations are important parameters. Nonlinear analyses show a significant increase in deformability and damping of the soil-structure system, implying a consequent reduction of the seismic forces on the structure. As a result, the base shear values dropped by approximately 57.56%, 44.46%, and 69% in the 3, 6, and 9-story frames, respectively.

1. INTRODUCTION

In the past 50 years, different research focused on how structural response and the ground response are affecting each other mutually, causing changes in the dynamic characteristics of each part of the coupled soil-structure system. This interaction between the underlain soil and the structure is governed by the so-called kinematic and inertial interactions. During this interconnection, loads, stresses, and strains are transferred between soil and structure. The interaction of the soil with the structure has been largely explored the assumption of material and geometrical linearity of the soil. Nevertheless, for moderate or strong seismic events, the maximum shear strain can easily reach the elastic limit of the soil behavior. Considering soil-structure interaction, the nonlinear effects may change the soil stiffness at the base of the structure and therefore energy dissipation into the soil. Consequently, ignoring the non-linear characteristics of the dynamic soil-structure interaction this phenomenon could lead to erroneous predictions of structural response.

Based on the literature, the direct method is currently the most important approach used for modeling the interaction soil-foundation-structure problems under seismic wave motions. Referring to this approach, the SSI could have beneficial or detrimental effects on different structural types for different soil conditions under different seismic inputs (Abdel Raheem et al. 2015; Ghandil and Behnamfar 2017; Fatahi et al. 2018). The common assumption that the lengthening of natural period

phenomenon, induced by the SSI invariably, results in a reduction in internal efforts is not justified because several parameters come into consideration (Kraus and Džakić 2013). On the one hand, the properties of soil foundation, particularly its behavior when subjected to the upward propagating seismic waves, affect significantly the response of the structure, such as its natural frequency, damping and the deformability of the soil-foundation-structure system, as well as the intensity and the distribution of seismic forces along the height of the structure, compared to the fixed-base building (Kabtamu et al. 2018; Echebba et al. 2021; El-Hoseiny et al. 2021 ; Zomorodian et al. 2021; Outayeb et al. 2023). On the other hand, the frequency content of the seismic waves plays an important role in changing the seismic behavior of structures. Indeed, when the frequency content of the seismic ground motion is close to that of the SSI system, the unexpected amplification of the seismic response is more marked for resonance case (Çelebi et al. 2012). This possible resonance between different parts of the coupled system involved in SSI mechanism must be considered in any analysis of structures subjected to seismic motions; otherwise, unpredicted seismic damage can occur. This is what happened for low- and mid-rise structures with shallow foundations resting on elasto-plastic soft soil, where their seismic performance level changed from a life-safety level to a near-collapse level. Also, radiation damping of the foundation can be affected by the soil plasticity (Torabi and Rayhani 2014; Tabatabaiefar et al. 2014), and as concluded by Scarfone et al. (2020), the presence of a very soft layer in the soil deposit leads to a stronger increase of the seismic demand of the building. By looking at the free field

seismic response of the soil medium, the peat layer reduces the high frequency components and amplifies the low frequency components of the seismic motions. The very soft layer acts as a natural damper for the maximum acceleration at the surface of the soil.

According to what is aforementioned above and as a concern for the difference between analyses under equivalent linear and fully nonlinear soil models, Çelebi et al. (2012) highlighted that the constitutive numerical material model assumed for underlying soil plays a key role on the seismic response of structures. However, very few works have analyzed the effects of nonlinear behavior of the supporting soil on the seismic response of structures (Tabatabaiefar et al. 2014).

The aim of this work is to study the effects of SSI on the seismic response of low and mid-rise RC buildings on shallow foundations underlying a very soft soil layer. Emphasis is given to possible effects induced by nonlinear behavior of the supporting soil on the overall dynamic response of the soil-structure system. Different features of the SSI are compared to the linear case: modification of the amplitude and frequency content of the waves propagated into the soil, fundamental frequency, energy dissipation in the soil and the response of the soil-structure system. Through these parametric studies, we investigate how depending on the soil properties, frequency content of the soil response could change significantly due to the soil nonlinearity and how the peaks of the transfer function between free field and outcropping responses can shift and influence the structural response.

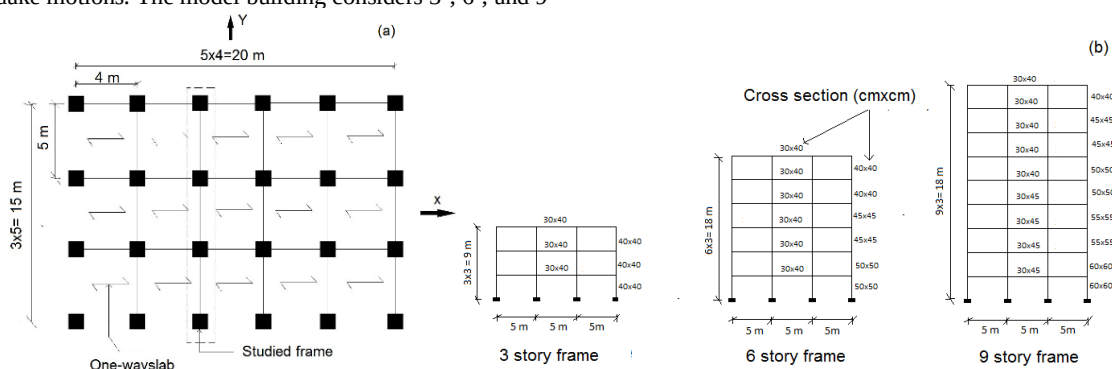
It is important to highlight that this study is based on the simplified assumption of a linear behavior of the structural elements, whereas two different constitutive models are taken into account- including elastic linear and an elasto-plastic hysteretic constitutive model for the soil. Linear and nonlinear dynamic analyses were conducted in the time domain using the finite difference code FLAC-2D. The seismic response of buildings is determined using the global method by assuming fixed support at the base of the structure and when a structure is on relatively soft soil, subjected to three strong time-history earthquake motions. The model building considers 3-, 6-, and 9-

story RC moment-resisting frames designed according to the Algerian seismic code RPA99/Version 2003. The study also extends its scope to assess the impact of the contribution of the secondary modes of vibration of buildings on the seismic response of soil-structure systems depending on the soil medium behavior.

2. DESIGN CONSIDERATIONS

As depicted in Fig. 1a, we consider a typical and ordinary model building plan in Algeria. A set of three structural models, consisting of 3, 6, and 9-story RC building frames are adopted, representing conventional types of low and mid-rise moment resisting building frames. Typical elevation views with a typical story height are shown in Fig. 1b. The structures chosen are regular in elevation and in plan to remove secondary effects due to irregularity. Columns and beams of frames are considered to be made of reinforced concrete with same material properties.

The structural design was performed in accordance to BAEL 91 (1992) and Algerian Seismic Design Code Provisions RPA 99/version 2003 (2003) under the design seismic action of $PGA = 0.25\text{ g}$, which corresponds to a high seismicity zone (Zone III), soil type S3 (soft soil), a quality factor of 1, and a viscous damping ratio of 5%. A seismic behavior factor of 5 was adopted for frames without masonry infill. The gravity loads assigned to the buildings were the own weight of structural components, including the reinforced concrete beams, columns and the slabs, and the live loads they support. Therefore, the imposed load in weight calculation, are uniform live load of $LL = 2.5\text{ kN/m}^2$ and roof live load of $LL = 1.0\text{ kN/m}^2$. Also, a dead load of $LD = 5.1\text{ kN/m}^2$ and a roof dead load of $LD = 5.8\text{ kN/m}^2$ are adopted. A characteristic cylinder strength of 25 MPa for concrete and a yield strength of 500 MPa for steel are utilized. The structures are founded through shallow foundations on an idealized homogeneous 30 m deep soft clay layer. The foundations are of 0.5 m thick and 15 m length and assumed to be located close to the ground; the effect of the embedment depth of the foundation has been ignored in soil-structure interaction system.



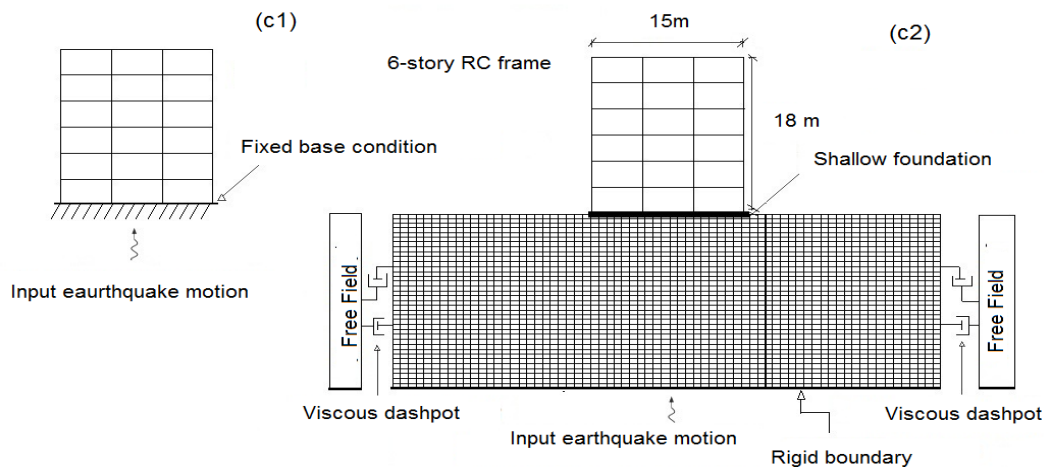


Figure 1. a. Typical floor plan for model buildings of 3-, 6-, and 9- stories; b. Typical model building frames 3-, 6-, and 9- stories; c. Overview of the components of the numerical model: c1- fixed base model; c2- the finite difference modeling: plane-strain conditions are assumed, taking account of soil inelasticity

The soil we are concerned with is basically a very simple one. A system of horizontal soil layer, bounded by the free surface and below by a semi-infinite elastic medium representing the bedrock, is postulated. The soil deposit is located at El Biar, in Algeria with the geotechnical characteristics based on the available in-situ tests and illustrated in Table 1 (Saci, 2011).

With a constant shear velocity V_s of 180 m/s, this soil is classified as a very flexible soil according to the Algerian seismic code RPA2003.

Mass density (kg/m^3)	Shear velocity (m/s)	Shear modulus (MPa)	Bulk modulus (MPa)	Friction angle	Cohesion (KPa)
1520	180	49.2	90.1	10°	60

Table 1. Details of soil parameters

2.1 Modeling the structure

A two-dimensional representation is selected in the light of the symmetry of buildings and the limited significance of torsional effects. As a result, each frame model in 2D modeling process represents the same characteristics as the whole parallel building frames in perpendicular direction. The superstructure supported by an elastic concrete foundation, is installed in a single stage after the model is in equilibrium. As mentioned by Rayhani and Naggar (2008) and Yue and Wang (2009), the behavior of the elements of the foundation remain elastic under static and dynamic conditions in the soil-structure interaction analysis. While Slabs are not modeled explicitly in FLAC-2D software, their weight and the live load they support were included in the structural model by assigning their reaction to the carrying girders. Consequently, in both the static and seismic analyses, to consider the dead load and live load of the slabs in each story, the mass density of the beams was enhanced in accordance with Eq. (1) (Yeganeh et al. 2015). The mass density of the reinforced concrete columns was set at 2500 kg/m^3 .

$$(DL + \beta \cdot LL) \times \text{Spacing} = \text{Area} \times \rho \quad (1)$$

Where: DL = Dead Load,
 LL = Live Load,
 Spacing = element spacing in out-of-plane direction, used to scale properties to approximate the 3D effect,
 β = Live Load reduction factor, due to the low probability of simultaneity of earthquake and the existence of the whole Live Load in the building,

Area = cross-sectional area of the beam,
 ρ = mass density.

Before proceeding with the dynamic time history analysis, an initial static stage is performed, during which the construction of the structure is simulated and the system is brought to an initial equilibrium state under only gravity loads. As stated by Wegner and Zhang (2005), the generally considered seismic wave model is that of volume waves propagating vertically from assumed rigid horizontal bedrock. Subsequently, dynamic loading is applied at the base of the model as an acceleration excitation, assuming horizontally polarized shear waves propagating vertically.

A critical damping ratio of 5% is used to reproduce the structural damping. Roy and Dutta (2010) investigated the effects of the damping due to SSI on the structural response by varying the critical damping from 2% to 30%. They concluded that high values of damping do not give significant disparities compared to critical damping of 5%. The frequencies of the first and the second modes were selected after running the modal analysis using SAP2000 software. The corresponding periods are listed in Table 2.

Mode number	3-Story frame		6-Story frame		9-Story frame	
	Period T(s)	Modal mass (%)	Period T(s)	Modal mass (%)	Period T(s)	Modal mass (%)
1	0.42	86	0.77	80	1.00	76
2	0.12	11	0.25	12	0.35	13
3	0.07	3	0.13	5	0.19	5

Table 2. Periods of significant modes in which almost 90% of the mass participated in the dynamic response of buildings

2.2 Modeling the soil

For modeling the infinite soil surrounding structure, to consider the effect of wave propagation sufficiently far from structure, Rayhani and Naggar (2008) concluded that the horizontal distance of lateral boundaries of the soil should be at least five times the width of the structure in order to minimize boundary effects on the building response during both the static and dynamic stages. In addition, it is well known that the seismic local site effects are influenced primarily by the properties of the top 30 m of the soil.

Therefore, in this study, the soil medium at the site of interest was truncated into a small domain with the dimensions of 75 m by 30 m, and discretized into 2250 two-dimensional plane-strain quadrilateral elements.

The procedure of quiet (viscous) boundaries developed by Lysmer and Kuhlemeyer (1969) is activated in order to represent the effect of the truncated soil. The independent dashpots in the normal and shear directions are coupled to the free-field columns at the sides of the model to reproduce the free-field motion that would exist in the absence of the structure. For modeling the underlain bedrock, the rigid bedrock boundary condition is assumed. It is the most suitable for modeling bedrock for soil-structure interaction analysis as stated by Kocak and Mengi (2000). The systems were considered under the two alternative conditions of rigid foundation and soil-structure interaction as shown in Fig. 1c. This figure illustrates a 6-story, 3 span reinforced concrete moment-resisting building frames.

2.2.1 Soil inelasticity

In the soil-structure interaction field, several models are employed by researchers to efficiently describe the behavior of soil mechanisms. In case of soil at the site of interest, the limited tests outcome being a fateful area of determining the soil parameters, which make impossible use of complex constitutive models. Therefore, to further explore the effect of soil plasticity on seismic response of structure models, two scenarios were assumed for the soil deposit, namely: the soil could behave as an isotropic, linearly elastic material with no failure limit or as an elastic-perfectly plastic material with a Mohr-Coulomb failure criterion and a standard non-associated flow rule, with angle of dilatancy $\psi=0$ for inelastic soil analysis. The value of $\psi=0$ corresponds to an elastic-perfectly plastic material, where there is no dilatancy when the material reaches plasticity. This is often the case for clays or sands of low or medium density under fairly high stress. Thus, both elastic and plastic soil behavior can be captured by the model during dynamic analysis process.

This model is commonly used in soil-interaction studies and requires only a few material parameters to describe soil behavior. Alternatively, the nonlinear effects in the soil can be described by the modulus reduction curve and damping ratio curve. These curves show the relationship between shear modulus and the damping corresponding to the cyclic shear strain level in the soil.

2.2.2 Determining the soil damping and the shear modulus ratio of soil (G/G_0)

In soil and rock, natural damping is mainly hysteretic and the nonlinear effects in the soil medium can be captured using the modulus reduction and damping ratio curves. Several built-in tangent modulus functions are available in FLAC-2D library to implement hysteretic damping by representing the variation of the damping ratio and shear modulus reduction factor with cyclic strain using fitting parameters which allow generate backbone curves for different soils as required. In this study, nonlinear and hysteretic behavior was introduced for stress path within the yield surface through a hysteretic model, extending to general strain conditions the unloading-reloading rules (Masing, 1926).

The constitutive soil model is entirely defined by two strength parameters (friction angle and cohesion), two elastic parameters (the small strain shear modulus, G_0 , and the Poisson's ratio, ν), and three parameters controlling the shear modulus degradation curve (a , b and x_0), as stated by Eq. (6):

$$\frac{G(\gamma)}{G_0} = \frac{a}{1 + \exp \left[-\frac{\log_{10} \gamma - x_0}{b} \right]} \quad (6)$$

Fig. 2 illustrates the obtained backbone curves by fitting parameters $a=1.017$, $b=-0.479$ and $x_0=-1.249$ representing the backbone curves suggested by Seed and Sun (1988) for clayey soils. In addition, amount of 0.2% of viscous damping at $f=1.5$ Hz was assigned to the soil elements to reproduce small strain frequency range of interest and to remove the high-frequency noise deriving from the numerical integration (Chopra, 2007).

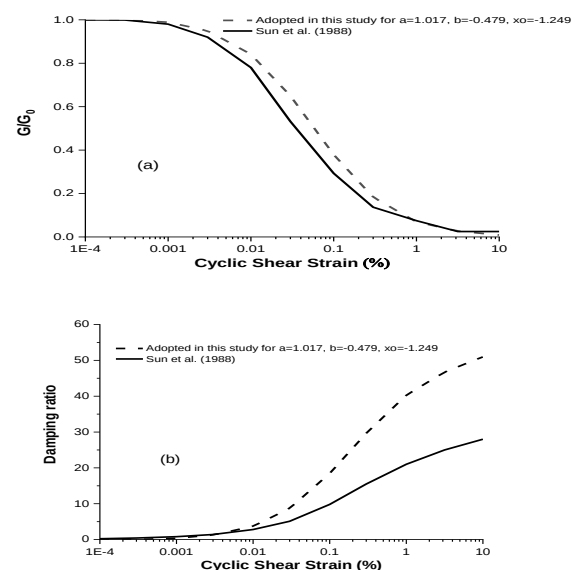


Figure 2. Calibration of backbone curves for soil (soft clay) against published curves (Seed and Sun 1988): a- $G/G_{max} - \gamma$, b- The material damping ratio $-\gamma$

3. DYNAMIC TIME - HISTORY ANALYSIS

An ensemble of three well known earthquakes, taken from the Canadian Association for Earthquake Engineering (CAEE) (Naumoski, 1988) are used as seismic excitation of the systems. Names and seismic parameters of the earthquakes are presented in Table 3 and the corresponding elastic acceleration response spectra are shown in Fig. 3. This group of earthquakes is selected in terms of the peak ground acceleration to peak ground velocity (A/V). This is motivated by the fact that the one major factor that has significant effects on the structural response is the frequency content of the record motions; factor that can be precisely estimated by the A/V ratio.

The selected ground motions are scaled according to the PGA scaling method (Choopool and Boonyapinyo, 2011). So doing, selected ground motions were scaled to the intensity of the design spectrum of the Algerian seismic code RPA 99/version2003 for a $PGA = 0.25g$. As stated by Joyner and Chen (1975), prescribing the ground motion at the base of the soil column is equivalent of assuming infinite rigidity in the underlying medium. In the following sections, we present the response of the systems with fixed and flexible base. Of special interest is the effect of soil plasticity on the seismic response of RC frames. The free-field seismic response analysis results are first presented. The results are presented in the form of the average of the maximum values under the three ground motion records.

Earthquake	Date	Site	Comp	Mag. (Ms)	Max. Acc. A (g)	Max. Vel.V (m/s)	A/Vratio*
San Fernando-1 California	09/02/1971	Lake Hughes	Station 4 S21W	6.4	0.146	0.085	1.72
Imperial Valley California	18/05/1940	El Centro	S00E	6.6	0.348	0.334	1.04
San Fernando-2 California	09/02/1971	3470 Wilshire Blvd L A	S90W	6.4	0.114	0.186	0.61

Table 3. Ground motions used in time-history analysis

* $A/V > 1.2$: high frequency content; $0.8 < A/V < 1.2$: intermediate frequency content; $A/V < 0.8$: low frequency content (Naumoski, 1988)

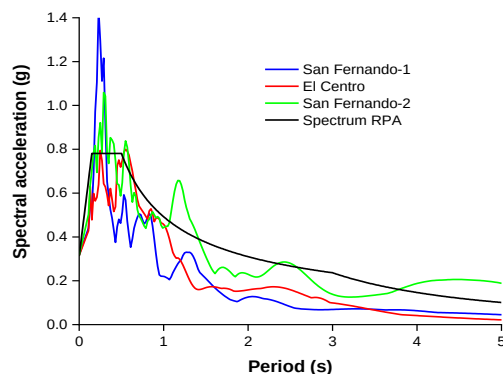


Figure 3. Elastic spectra of the real earthquake records used for analysis of the two systems, along with their elastic spectra and the design spectrum of the investigated buildings (RPA99/Version 2003)

The selected ensemble of 3 records covers high frequency content (San Fernando-1 in California), intermediate frequency content (Imperial Valley in California) and low frequency content (San Fernando-2 in California).

3.1 Free-field response

A comparison of the acceleration response spectra at the surface of the soil deposit is illustrated in Fig. 4a. As expected, while the soil is considered elastic (Fig. 4a1), the free-field responses are amplified with respect to the bedrock. This amplification can be attributed to the fact that the seismic wave energy is transferred more efficiently from the stiffer soil to the softer soil layer overlying bedrock. As a result, the seismic demand on structures is expected to be increased. Moreover, considering that the

dominant periods of the fixed-base structures are 0.42s, 0.77s and 1s for the 3-, 6- and 9-story frame, respectively (Table 2), to which correspond the average spectral accelerations of 1.77g, 2.4g and 1.09g, the inertia forces of the 6-story frame are expected to be higher than that of the two other frames. In marked contrast, by considering an elasto-plastic soil behavior (Fig. 4a2), the observed effect is opposite. An attenuation phenomenon of the free field acceleration is observed up to period $T = 1s$ regardless to the frequency content of the applied motions which is a result of the decline in soil stiffness and escalation in its material damping as a consequence of soil dissipation capacity. We can attribute this attenuation to the filtering capacity of the plastic soil through its hysteretic behavior. In other words, when the soil exhibits plastic behavior, part of the seismic wave energy is dissipated in the form of heat due to irreversible ground deformation and a loss of energy and, a reduction in the seismic acceleration of the ground motion at the surface is observed. Consequently, a decrease of the seismic demand on structures is expected. For the sake of clarity, Fig. 4b compares the maximum acceleration along the depth of the soil profile, with the two alternatives of soil behavior. It can be clearly seen that the elastic soil amplified the applied motion at the bedrock (Fig. 4b1). In stark contrast, with plasticity effect, the result shows a slight amplification in the first 5 meters followed by a decrease in the maximum acceleration at the surface (Fig. 4b2).

Besides the response spectra at surface and maximum acceleration mobilized within the soil deposit, we extend the comparison for the maximum deformation profile. Fig. 4c shows the maximum shear strain mobilized along the depth of the soil deposit with the two alternatives of the soil behavior. It can be seen that the inelastic soil experienced large shear strain. Thus, one might expect that the overall movement of the structure resting on a plastic soft soil is more pronounced than that of the structure resting on soil behaving as elastic material.

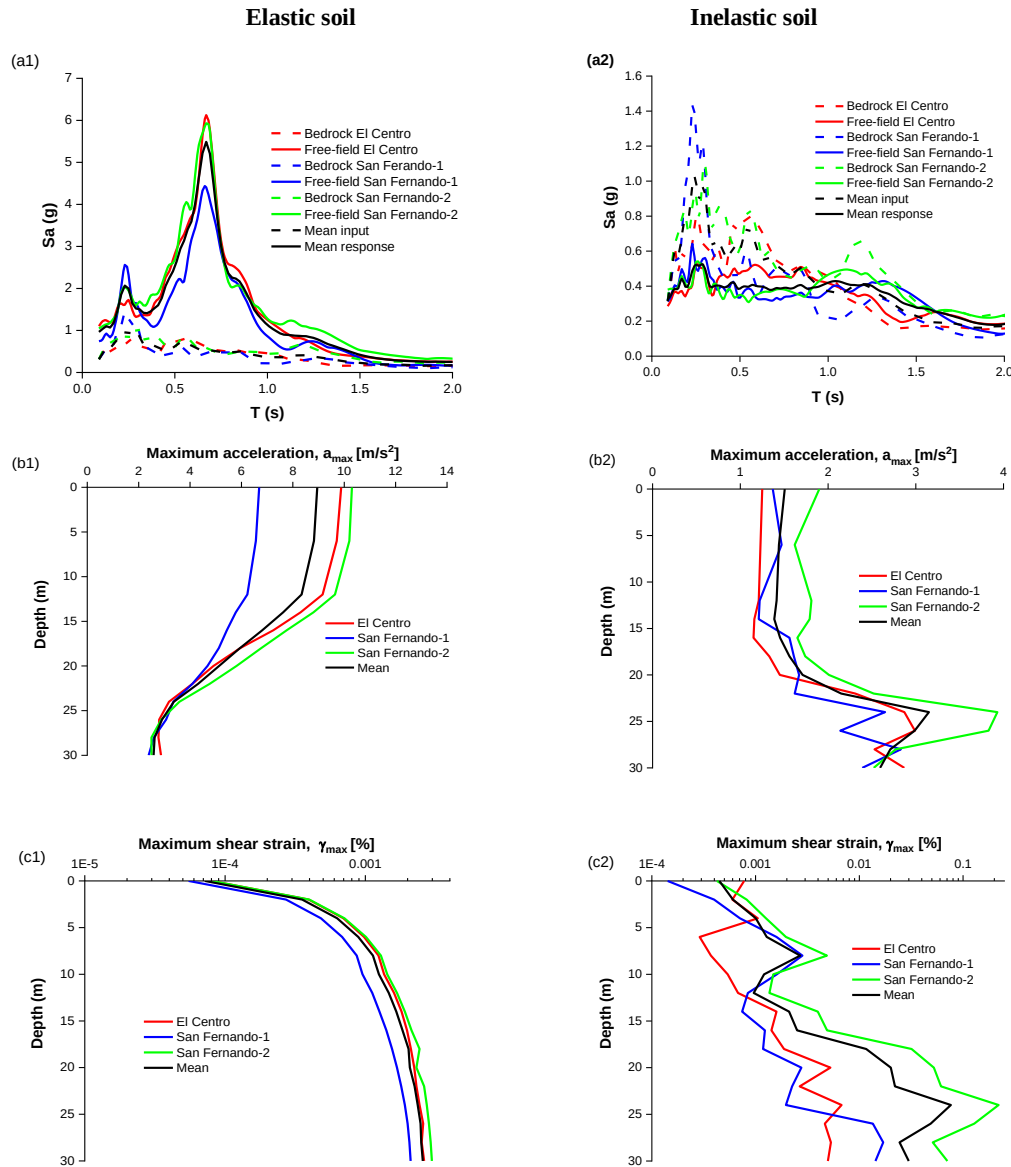


Figure 4. Comparison of the response of the two alternatives of the soil behavior subjected to three earthquakes: -**a1, a2** acceleration response spectra at surface. With elastic soil, the free-field responses are amplified with respect to the bedrock. As a result, the seismic demand on structures is expected to be increased. In marked contrast, by considering an elasto-plastic soil behavior, an attenuation phenomenon is observed up to period $T = 1$ s. -**b1, b2** maximum acceleration. the elastic soil amplified the applied motion at the bedrock. In stark contrast, with plasticity effect, the result shows a slight amplification in the first 5 meters followed by a decrease in the maximum acceleration at the surface. -**c1, c2** maximum mobilized shear strain. The inelastic soil experienced large shear strain. One might expect that the overall movement of the structure resting on a plastic soft soil is more pronounced than that of the structure resting on soil behaving as elastic material.

3.2 Full dynamic interaction results

In this section, we compare the response of the systems of two alternatives for: (i) elastic soil and (ii) inelastic soil. The SSI effects including plasticity behavior of the underlying soil medium are investigated.

In Fig. 5 the comparison is portrayed in term of the frequency-dependent transfer functions, $|F| = |U_{STR}/U_{ff0}|$, between the horizontal roof displacement (U_{STR}) and the free-field surface motion (U_{ff0}). It can be seen that the seismic response of the

investigated frames is highly dependent on the behavior of the underlying soil. As seen in case of elastic soil, an amplification response is observed, especially for the 6-story frame (Fig. 5b1), while in case of the inelastic soil, a subsequent reduction of the response is denoted for the three structures. It has also been observed that this reduction happens mostly in the first mode of vibration for the 3- and 6-story frames with respective natural frequencies lower than the corresponding fixed-base models (i.e., $f_{1, SSI} < f_{1, FIX}$). For the 9-story frame, this reduction occurs in the three modes of vibration, but it is still more pronounced in the first mode of vibration.

It is worth to mention that the overall increase in deformability of the soil-foundation-structure system compared to the fixed-base structure due to the SSI effects is observed regardless of the constitutive modeling of the soil behavior.

This can be attributed to the fact that the natural frequencies of flexible base models are lower than those of fixed base models.

However, in terms of the overall increase in damping of the system, the inelastic soil has a stronger effect due to its ability to dissipate seismic energy through its hysteretic behavior. This is directly inferred to the reduction of the seismic response of the flexible base structures.

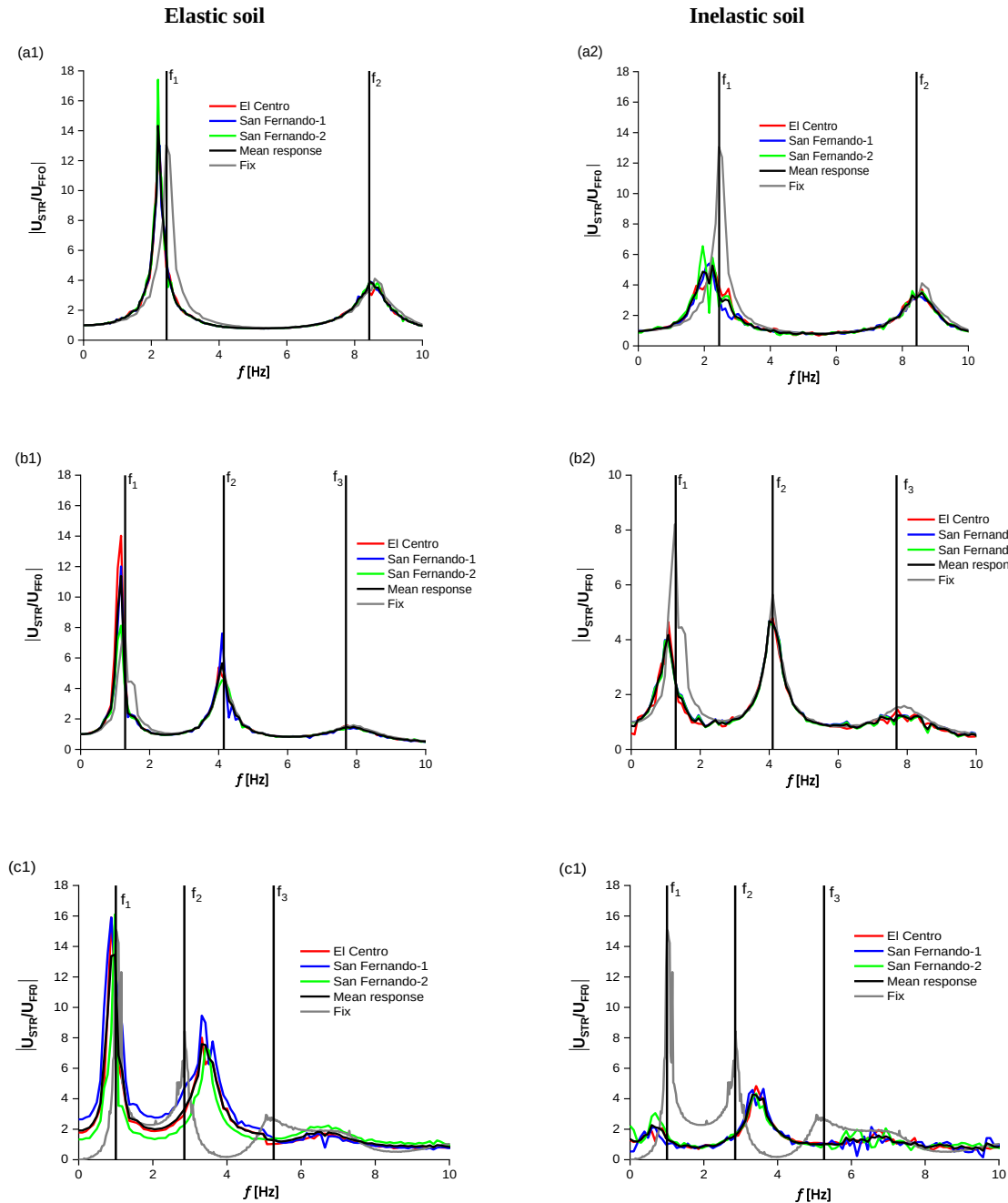


Figure 5. Comparison of the transfer functions between the displacement of the roof and the free field motion computed for the two alternatives of the soil behavior subjected to three earthquakes:

-a1, a2 3-story frame, -b1, b2 6-story frame, -c1, c2 9-story frame.

In case of elastic soil, an amplification response is observed, especially for the 6-story frame, while in case of the inelastic soil, a subsequent reduction of the response is denoted for the three structures. This reduction happens mostly in the first mode of vibration for the 3- and 6-story frames with respective natural frequencies lower than the corresponding fixed-base models (i.e., $f_{1,SSI} < f_{1,Fix}$). For the 9-story frame, this reduction occurs in the three modes of vibration, but it is still more pronounced in the first mode of vibration.

Still with the aim of arriving at a better understanding of the way in which the seismic response of the frames is influenced by the behavior of the underlying soil, the distribution of the story shears over the height is presented here. The mean values of the maximum story shears for the two alternatives are compared in Fig. 6. It can be seen that in elastic soil case (Figs. 6a1, 6b1, 6c1), SSI increases the seismic demand of structures, in terms of story

shear, as anticipated based on the results of the free-field analyses. When analyses are performed for structures supported by soil layer including plasticity effect (Figs. 6a2, 6b2, 6c2), as expected, SSI reduces the story shears compared to fixed-based models, due to the increased deformability and damping of the system as aforementioned above.

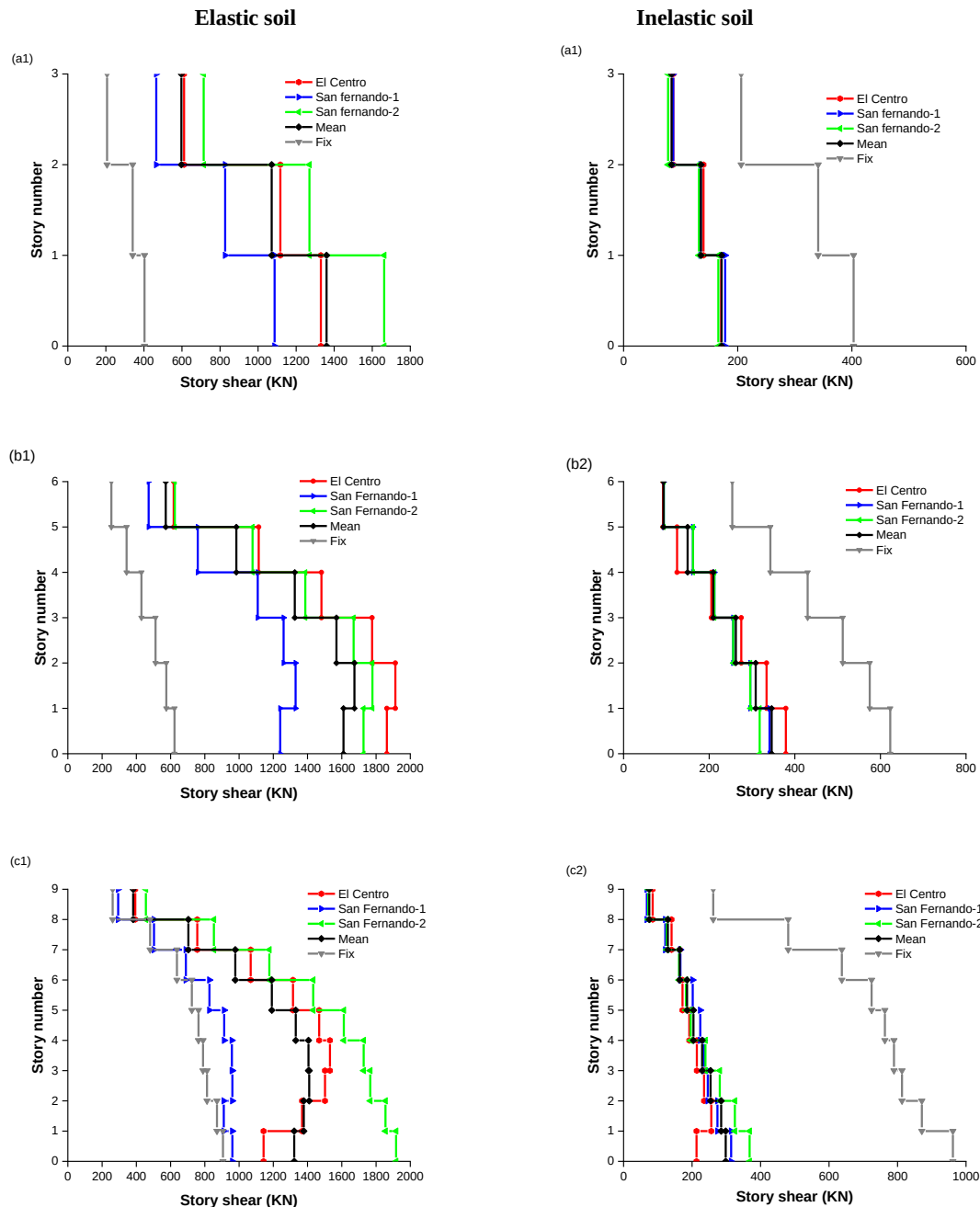


Figure 6. Comparison of the mean value of the maximum story shear forces computed for the two alternatives of the soil behavior subjected to three earthquakes: -a1, a2 3-story frame; -b1, b2 6-story frame; -c1, c2 9-story frame.

In elastic soil case, SSI increases the seismic demand of structure. When structures are supported by soil layer including plasticity effect, SSI reduces the story shears compared to fixed-based models, due to the increased deformability and damping of the system. The seismic base shear of the 6-story frame is superior regardless of the constitutive modeling of the soil behavior. This can be attributed to the significant contribution of the second mode of vibration of the 6-story frame compared to the other frames, especially the 9-story frame.

By looking at the response of the flexible base frames, it can be seen that the seismic base shear of the 6-story frame is superior when resting on elastic or inelastic soil. This result has been already predicted in the section dealing with free-field analyses. This can be attributed to the significant contribution of the second mode of vibration of the 6-story frame compared to the other frames, especially the 9-story frame. Indeed, it can be seen from the mean elastic response spectra computed at the surface of the inelastic soil layer that, for the 6-story frame, the spectral acceleration corresponding to the second mode of vibration is of 0.52g, while for the 9-story frame, the corresponding value is of 0.4g (Fig. 7). Thus, and contrary to popular assumption, a structure with a low seismic weight (6-story in our case) might have a considerable seismic demand when compared to a structure with a high seismic weight (9-story in this study).

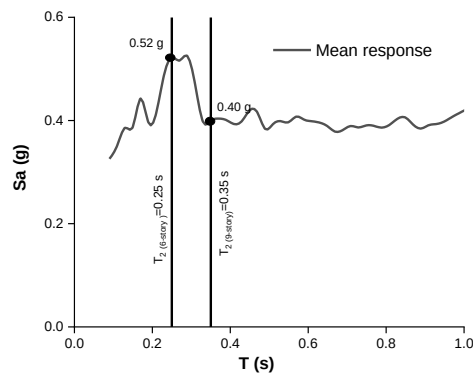


Figure 7. Mean acceleration response spectra computed at the surface of inelastic soil medium

For the 6-story frame, the spectral acceleration corresponding to the second mode of vibration is of 0.52g, while for the 9-story frame, the corresponding value is of 0.4g. Contrary to popular assumption, a structure with a low seismic weight might have a considerable seismic demand when compared to a structure with a high seismic weight.

4. SUMMARY AND CONCLUSIONS

In the present paper, the soil plasticity that can affect the seismic response of RC frame structures was assessed numerically by performing linear and non-linear dynamic analyses in the time domain using the finite difference code FLAC-2D. This study is based on the comparison of the results derived from analyses performed under two conditions of soil behavior. Comparisons are made at the free-field level as well as across the complete soil-foundation-structure system.

Numerical results revealed that, in case of elastic soil, free-field responses are amplified. As a result, the seismic demand on frame structures has increased in terms of story shears. However, when inelastic soil deformation develops, the attenuation phenomenon is observed, meaning that the seismic demand is significantly reduced. It is important to highlight that the 6-story frame presents the highest seismic base shear instead of the 9-story frame. This result emphasizes a critical factor related to the seismic vulnerability of frame structures. Indeed, it is commonly stated that the vulnerability of frame structures is directly proportional to the number of stories. However, as stated in this study, the 6-story frame has a larger seismic demand than the 9-story frame, particularly when underlain soil of structures is of inelastic behavior. As a result, we may conclude that the characteristics of the input motion, as well as the constitutive

modeling of the soil behavior, are also essential criteria in the evaluation of the seismic vulnerability of frame structures.

It is worth to mention that the overall increase in deformability of the soil-structure system compared to the fixed-base structure due to the SSI effects is observed for structures resting on soil medium regardless of the constitutive modeling of the material behavior. However, in terms of the overall increase in damping of the system, plastic soil has a stronger effect due to its ability to dissipate seismic energy through its hysteretic behavior. By analyzing these results, we find that there is a benefit to be gained, from an economic point of view, by using the dissipative capacities of the plastic soil behavior to significantly reduce the seismic design forces. In addition, the reduction of the base shear leads to the same reduction of stresses applied to the foundation, which also leads to a reduction in the cost of infrastructure. For the selected structures and soil profile of this work, the performed numerical simulations show that the shift of the fundamental frequency is not the only index to discriminate benefit from detrimental effects of SSI.

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