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HAL Id: hal-03776878
https://hal.science/hal-03776878

Submitted on 14 Sep 2022

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Abstract

In seismic performance based design context, engineers are faced to a difficult task to estimate the response of soil-structure interaction (SSI) systems. To accomplish this task successfully, all sources of random and epistemic uncertainties should be taken into account. However, the uncertain parameters have not the same influence on the model response; a sensitivity analysis is therefore required. This article treats the two following aspects: the first one is to perform a sensitivity analysis on all the parameters in order to study their influence on the structural response. The uncertainties effect is done by studying the sensitivity of the maximum structure displacement towards the used materials parameters variation (f_c', ε_{c0}, ε_{cu}, E_s, f_{sy}, a, ε_{su}, A, ξ) and soil properties (ξ_g, v) on the SSI seismic response. This study consists of determining, quantifying and analyzing how the outputs of the N2-SSI model are affected by input variables fluctuations. The second aspect is analysing the SSI system response by considering the correlation between the parameters (shear wave velocity and soil damping) and the influence of the lack knowledge of the uncertainties due to this correlation. The results of the sensitivity analysis indicate that the response of the structure is very sensitive to the concrete and steel parameters for larger values of the shear wave velocity. While, the soil damping and Poisson's ratio in the case of soil with shear wave velocity of 90 m/s, are the main inputs with the greatest influence on the maximum displacement output.

Keywords

seismic, soil-structure interaction, uncertainty, sensitivity analysis, concrete, steel

1 Introduction

The complexity of the soil–structure interaction (SSI) problem [1–6] accompanied with the inherent uncertainty propagation from model parameters describing the structure, the soil, and the earthquake motion characteristics has resulted in a somewhat controversial interpretation of SSI effects on the structural seismic response [7].

A variety of procedures to study the effects of uncertainty on the seismic response of a structure has been proposed in the literature. The most recent research works can be mentioned like Vamvatsikos and Fragiadakis [8] who used Monte Carlo simulations with Latin-Hypercube sampling to assess the effects of uncertainties in model parameters on collapse response of structures. Na et al. [9], Celik and Ellingwood [10], Celarec and Dolšek [11], Kim et al. [12]

studies reveal that uncertainties of the mass of the structure, the concrete strength, the columns yield rotation and the effective slab width have lesser importance.

Traditionally, the effects of inertial soil-structure interaction on buildings seismic response can be quantified by a period lengthening and increased damping of the system [13], and on this basis, it has been concluded and implemented in design codes [14, 15] that including SSI in the analysis has a beneficial or detrimental effects in the seismic response of structures. However, it has been also argued that the perceived beneficial role of SSI is an oversimplification of the reality and indeed is incorrect for certain soil–structure systems and earthquake motions [16, 17]. Thus, it has been recently shown that proper methods are

required for the study of uncertainty propagation from model parameters describing the structure, the soil, and the applied loads to structural responses by defining some performance limit states [18–20].

The above studies have treated different problems of structural uncertainties without introducing the effect of soil or soil-structure uncertainties in the system. To the authors' knowledge, only few studies have addressed the issue of the effect of uncertainties in SSI system. Moghaddasi et al. [21] evaluate the influence of foundation flexibility on the structural seismic response by considering the variability in the system and uncertainties in the ground motion characteristics. The obtained results illustrate the risk of underestimating the structural response associated with simplified approaches in which SSI and nonlinear effects are ignored. Moghaddasi et al. [22] define the correlation between soil, structure, and interaction effects on the structural response. Their study shows that the variation of soil shear wave velocity, shear wave velocity degradation ratio, structure-to-soil stiffness ratio, structural aspect ratio and system stiffness affect significantly variation in structural response.

In particular for systems considering soil–structure interaction, the effect of uncertainty on structural response is even more pronounced [23–24].

In this context, the current study presents a parametric sensitivity analysis on all the parameters in order to study their influence on the structural response. We first examined the influence of the parameters related to the structure materials used (concrete and steel) on the lateral displacement of the structures, and then the soil parameters (shear wave velocity and soil damping ratio).

The lateral displacement of the system is determined by the N2-SSI approach developed by Mekki et al. [7]. This approach is based on the N2 method introduced in Eurocode 8 [25]. N2-ISS method completes N2 method by introducing the effect of the soil on the seismic response. The authors have demonstrated the effectiveness of this method through a comparative study with other recognized methods (the temporal dynamic method, the BSSC code [15], Avilés and Pérez-Rocha [26].

Knowing that the variability of soil properties constitutes an important source of uncertainty in geotechnical analyses, we analyze the effect of this variability on the seismic response of a structure within the framework of the SSI. Our second contribution in this article is the analysis of the response of the SSI system by considering the correlation between these parameters and the influence of

the lack of knowledge of the uncertainties due to this correlation. The soil properties we are interested in here will be shear wave velocity and soil damping.

2 Sensitivity analysis of SSI model

The response of a structure to an earthquake is influenced by several parameters. However, these parameters do not all have the same level of influence on this response. In order to identify the parameters that have the most impact and to which the response of the structure is the most sensitive, a deterministic sensitivity analysis of the different factors has been performed. Indeed, the knowledge of the variables that have the most influence on the output (maximum displacement of the structure), will allow to target the efforts to improve the knowledge on the most influential input variables, and thus decrease the errors on this output.

There are different techniques for estimating sensitivity indices in the literature [27–29]. The approach we followed is based on the calculation of a deterministic sensitivity index representing the variations of a model output following a variation of an input parameter. Each input parameter is assigned a nominal reference value. The analysis is performed by varying the reference value of an input parameter, while fixing all other input parameters at their nominal values. By calculating the partial derivatives of the output functions with respect to the input variables, the sensitivity index noted S is obtained by the following relation:

$$S = \frac{\partial Y / Y}{\partial X / X}. \tag{1}$$

This indice quantifies the sensitivity of the output Y with respect to the input parameter X.

In this article, a sensitivity study of uncertain structural parameters (concrete and steel) and soil is carried out on the lateral displacement of the SSI system which is determined by the N2-SSI method. The main steps of this method are summarized in Fig. 1 and described in detail below.

3 N2-SSI method for seismic analysis of structures in interaction with the soil

The complex behavior of SSI together with uncertainties in soil and structure parameters, and in earthquake ground motion result in a significant controversy over the effect of SSI on structural response in both elastic and inelastic states. Simple procedures proposed in seismic regulations are not sufficient to properly evaluate the influence of SSI on the structural response. A simplified N2-SSI model has
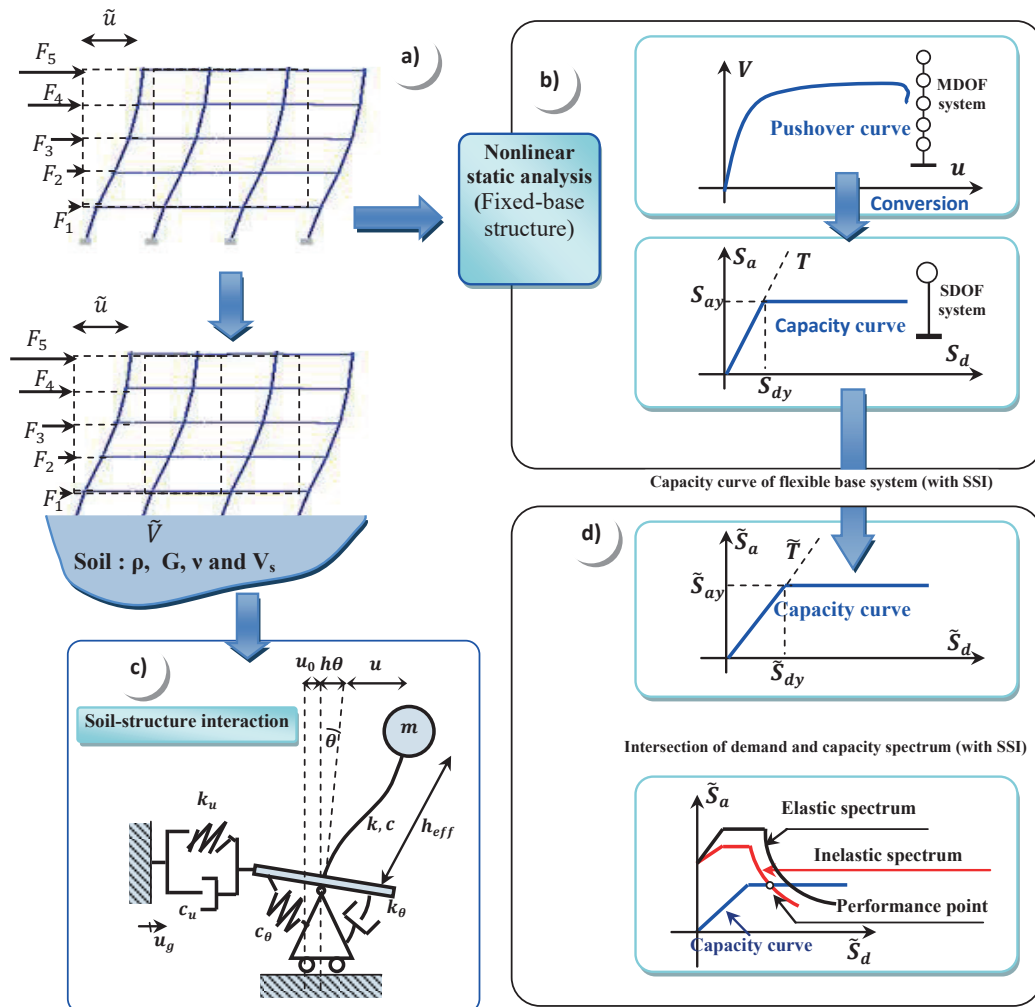
Fig. 1 Methodology of N2-SSI model

been proposed by Mekki et al. [7, 30] to resolve a complicated problem such as SSI. The N2-SSI method is an extension of the N2 method [31]. Both methods use standard pushover analysis to calculate the nonlinear response of a regular structure. The approach will consist in first determining the nonlinear response by the N2 method for the system without taking into account the SSI and then, introducing in a second step the effect of the SSI. The choice of the N2 method is due to its simplicity and its ability to determine the displacement of the structure with a "manageable" computational effort and reasonable accuracy. However, like any approximate method, the N2 method is subject to several limitations. It assumes that: (a) displacement shape is constant, i.e., it does not change during the structural response to ground motion and (b) the first mode is predominant. These are the basic and the most critical assumptions. The N2-SSI approach is illustrated in Fig. 1 and is organized in the following steps:

Step 1: Determination of the Pushover curve (base-shear force V vs. roof displacement u relationship) of a multi degree of freedom (MDOF) structure considered initially as fixed in its base.

Step 2: Evaluation of seismic demand for a fixed-based system (Fig. 1(b)). In this section, seismic demand is determined by using response spectra in acceleration-displacement format. The pushover curve (base shear V-roof displacement u) is converted to a capacity curve (spectral acceleration S_a-displacement S_d, Fig. 1(b)).

Step 3: Introduction of SSI through impedance functions. These functions describe the stiffness and damping characteristics of the foundation-soil system (Fig. 1(c)).

Step 4: The capacity curve of flexible base system (with SSI) is obtained by modifying the initial capacity curve built for a fixed-based structure. The intersection between the capacity curve (with SSI) and the inelastic spectra (with SSI) gives the performance point (Fig. 1(d)).

Fundamental period $\tilde{T}$ (Eq. (2)) of the flexible-base system is longer than fixed-base T system as well as effective damping $\tilde{\xi}$ (Eq. (3)), which is higher for the soil-structure system than for the structure alone [31].

$$\tilde{T} = T \sqrt{1 + k \left[\frac{1}{k_u} + \frac{h_{eff}^2}{k_\theta} \right]}, \tag{2}$$

$$\tilde{\xi} = \frac{T^2}{\tilde{T}^2} \xi + \left[1 - \frac{T^2}{\tilde{T}^2} \right] \xi_g + \left[\frac{T_u^2}{\tilde{T}^2} \xi_u + \frac{T_\theta^2}{\tilde{T}^2} \xi_\theta \right], \tag{3}$$

where $\xi = \pi c / kT$ and $T = 2\pi \sqrt{m/k}$ are the damping ratio and the period of the fixed-base structure, respectively; m, c and k are the effective mass, damping and stiffness of the structure, respectively; h_{eff} is the effective height of the equivalent SDOF; $T_u = 2\pi \sqrt{m/k_u}$ and $T_\theta = 2\pi \sqrt{m h_{eff}^2 / k_\theta}$ are the natural periods associated with rigid body translation and rocking of the structure, whereas $\xi_u = \pi c_u / (k_u \tilde{T})$ and $\xi_\theta = \pi c_\theta / (k_\theta \tilde{T})$ are the soil damping ratios for the horizontal and rocking modes of the foundation; and ξ_g is the soil damping.

The soil-foundation parameters are: horizontal stiffness and damping (Eq. (4)) and rocking stiffness and damping (Eq. (5)):

$$k_u = \frac{8}{2-v} G r_u; \quad c_u = \frac{4.6}{2-v} \rho V_s r_u^2, \tag{4}$$

$$k_\theta = \frac{8}{3(1-v)} G r_\theta; \quad c_\theta = \frac{0.4}{1-v} \rho V_s r_\theta^4, \tag{5}$$

where the soil is characterized by its Poisson's ratio v, shear modulus G and mass density ρ. The shear wave velocity for the medium is then given by $V_s = \sqrt{G/\rho}$, r_u and r_θ are the foundation radii computed separately for translational and rotational deformation modes to match the area A_f and moment of inertia I_f of the actual foundation (i.e., $r_u = \sqrt{A_f / \pi}, r_\theta = \sqrt[4]{A_f / \pi}$).

Lateral displacement $\tilde{u}_t$ Eq. (6) of the multiple-degree-of-freedom MDOF structure determined from performance point coordinates $(\tilde{S}_a, \tilde{S}_d)$ is larger in flexible base system (N2-SSI).

$$\tilde{u}_t = \tilde{S}_d \Gamma, \tag{6}$$

where $\tilde{S}_d (\tilde{T}, \tilde{\xi})$ is displacement of equivalent SDOF SSI system. Γ: Modal participation factor.

$$\tilde{S}_d (\tilde{T}, \tilde{\xi}) = \tilde{\mu} \frac{\tilde{T}^2}{4\pi^2} \tilde{S}_a (\tilde{T}, \tilde{\xi}) \tag{7}$$

The effective ductility $\tilde{\mu}$ will be equal to the structural ductility μ for infinitely rigid soil (for which ($\tilde{T} = T$) and to unity for infinitely flexible soil (for which $\tilde{T} = \infty$)).

$\tilde{S}_a (\tilde{T}, \tilde{\xi})$ is acceleration of equivalent SDOF SSI system, obtained by reducing the elastic acceleration $\tilde{S}_{ae} (\tilde{T}, \tilde{\xi})$ by the strength reduction factor $\tilde{R}_\mu (\tilde{T})$.

$$\tilde{S}_a (\tilde{T}, \tilde{\xi}) = \frac{\tilde{S}_{ae} (\tilde{T}, \tilde{\xi})}{\tilde{R}_\mu (\tilde{T})} \tag{8}$$

The strength reduction factor expression proposed by Vidic et al. [32] for fixed-base system, has been adjusted to flexible base system Eq. (8), this is a more rational way to assess nonlinear strength of SSI [33].

$$\begin{cases} \tilde{R}_\mu = (\tilde{\mu} - 1) \dfrac{\tilde{T}}{T_c} + 1 & \tilde{T} < T \\ \tilde{R}_\mu = \tilde{\mu} & \tilde{T} > T_c \end{cases} \tag{9}$$

$\tilde{\mu}$ is SSI equivalent ductility factor system proposed by Avilés and Pérez-Rocha [26] to fully characterize the nonlinear replacement oscillator.

$$\tilde{\mu} = 1 + (\mu - 1) \frac{T^2}{\tilde{T}^2}, \tag{10}$$

where T_c is soil characteristic period

4 Selected structure and modeling parameters
4.1 Description of selected structure
We will apply the approach to a case study, that of a reinforced concrete structure whose geometric and material characteristics are shown in Fig. 2. To model the constitutive laws of concrete and steel, respectively, the Kent and Park model [34] and the elasto-plastic model with hardening [35] were used.

The distribution of lateral forces depends on the shape of the first mode. We consider that the structure oscillates predominantly in the first mode and that its components are normalized in such a way that the displacement at the vertex is equal to 1. $\{\Phi\} = [0.2\ 0.4\ 0.6\ 0.8\ 1.00]$. The response spectrum used is that of the Algerian seismic regulations [36].

Regarding the soil characteristics, four types of soil are considered with different shear wave velocities (90, 300, 600 and 1350 m/s), the same Poisson's ratio $v = 0.3$, density $\rho = 1.9$ t/m³ and damping of soil $\xi_g = 10\%$ are considered. Square footings of 1.6 m sides are considered.

The introduction of the SSI effect in the N2-SSI approach is done by using the impedance functions (Eqs. (3) and (4)) to determine the effective period $\tilde{T}$ and the effective damping $\tilde{\xi}$ by Eqs. (1) and (2), respectively. These functions relate the geometric parameters of the foundation and the soil parameters such as shear wave velocity V_s, Poisson's ratio v and soil density ρ. The results of the application of the proposed approach on the studied structure are summarized in Table 1.
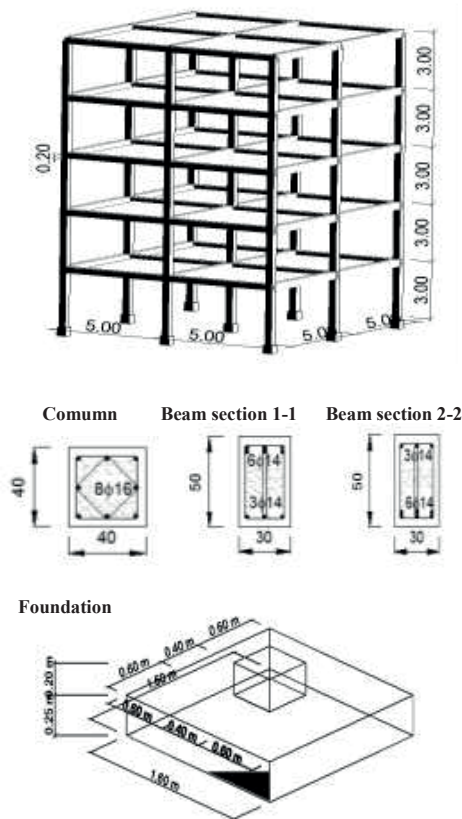
Fig. 2 Geometric characteristics of 5-story RC building

Table 1 shows the continuous decrease of the effective period $\tilde{T}$ when V_s values increase, due to the flexibility of the structure supports in comparison with the fixed base structure (the $\tilde{T} = T$ ratio amounts 1.60 for $V_s = 125$ m/s and amounts 1 for $V_s = 1350$ m/s. This is accompanied by the dissipation of a considerable amount of the vibrational energy due to the frequency-independent material damping due to the internal friction. This means that the period does not only depend on the height of the structure but also on the soil-structure interaction.

In the Table 1, one can see that for a soil shear wave velocity of 125 m/s, the effective damping is 1.50 times larger than the structure damping. One can also observe that when V_s takes value of 1350 m/s, the flexible base damping $\tilde{\xi}$ is equal to the viscous damping of the structure ξ, which clearly indicates there are no damping SSI effects in rock soil case.

4.2 Sensitivity analysis of the parameters related to the materials of the structure – method

The sensitivity analysis performed on the maximum displacement of the structure is performed by varying the twelve parameters related to the characteristics of the materials used listed in Table 2 and observe their effect on the displacement for two levels of the same earthquake (two different values of PGA):

PGA = 0.1 g corresponding to a weak earthquake in order to analyze the elastic behavior of the structure.

PGA = 0.6 g for a strong earthquake causing an elastoplastic behavior of the structure.

We have chosen the model developed by Kent and Park [34] (Fig. 3(a)). It allows to simulate efficiently the behavior of confined and unconfined concrete. This model shown in Fig. 3, is composed of an ascending parabolic portion until the strain reaches the strain corresponding to the maximum strength in compression of concrete ε_{c0} and then a descending linear portion for higher strains. A sensitivity analysis was performed on the parameters of this model for confined as well as unconfined concrete, namely: the concrete compressive stress f_c', the peak strain ε_{c0} corresponding to the concrete compressive stress, and the ultimate strain ε_{cu}.

The steel is modeled by an elastoplastic law with kinematic strain hardening [34] (Fig. 3(b)). The behavior of the steel is symmetric in tension/compression and characterized by an elastic phase until plasticization. A sensitivity study considered 4 model variables: the elastic modulus of the steel E_s, the yield stress of the steel f_{sy} [37], the strain hardening factor α, and the ultimate strain ε_{su}.

Table 2 summarizes the variables considered, the reference values and the variation intervals. The following paragraphs detail the results of the sensitivity analysis, which will be summarized next.

Figs. (4) and (5) are plotted by varying according to the values mentioned in Table 3.6, then the sensitivity study (Figs. (6) and (7)) is performed on the SSI system using the pushover curves related to the variation of each parameter.

Table 1 Variation of $\tilde{T}/T$ and $\tilde{\xi}/\xi$ for 4 soil types

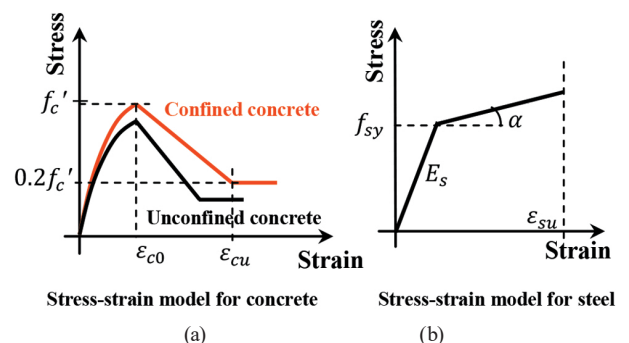| V_s [m/s]	125	300	600	1350
T [s]		0.82		
ξ [%]		5		
$\tilde{T}/T$	1.60	1.20	1.08	1.00
$\tilde{\xi}/\xi$	1.50	1.25	1.02	1.00

Fig. 3 Material constitutive laws; (a) Concrete; (b) Steel

Table 2 The different parameters of the models: confined concrete, unconfined concrete, and steel as well as their maximum and minimum variations

Materials	N°	Parameters	$(X)^-$	$(X)_{Ref}$	$(X)^+$	$(\partial X/X)^-$ in %	$(\partial X/X)^+$ in %
confined concrete	1	f_c' (MPa)	25	30	40	-16.67	+33.33
	2	ε_{c0}	0.001	0.002	0.003	-50.00	+50.00
	3	ε_{cu}	0.008	0.014	0.020	-42.86	+42.86
unconfined concrete	4	f_c' (MPa)	20	25	30	-20.00	+20.00
	5	ε_{c0}	0.001	0.002	0.003	-50.00	+50.00
	6	ε_{cu}	0.004	0.006	0.008	-33.33	+33.33
Steel	7	E_s (GPa)	205	210	215	-9.52	+9.52
	8	f_{sv} (MPa)	300	400	500	-25.00	+25.00
	9	α (%)	1	3	5	-66.67	+66.67
	10	ε_{su}	0.0079	0.0143	0.0220	-33.33	+33.33
Quantity of reinforcement	11	A (mm²)	1447.6	1608.5	1769.3	-10.00	+10.00
			1246.9	1385.4	1523.9	-10.00	+10.00
Damping of the structure	12	ξ (%)	2	5	10	-60.00	+100.00

$(X)^-$: Minimum value that the parameter can take, $(X)_{Ref}$: Reference value and $(X)^+$: Maximum value that the parameter can take
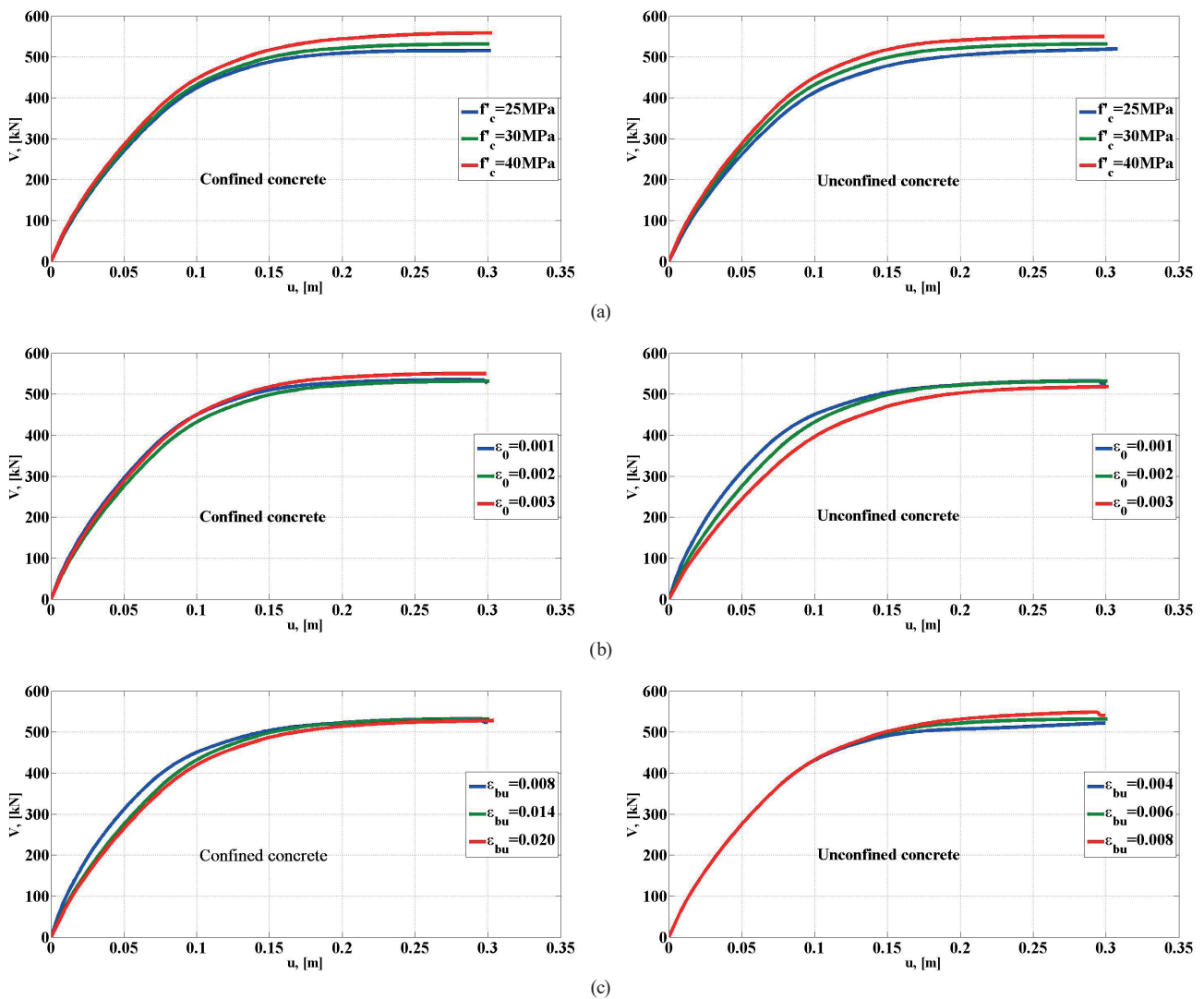
Fig. 4 Influence of the concrete parameters of the structure on the Pushover curve; (a) concrete compressive stress, (b) peak strain corresponding to concrete compressive strength ε_{c0} and (c) ultimate deformation of concrete
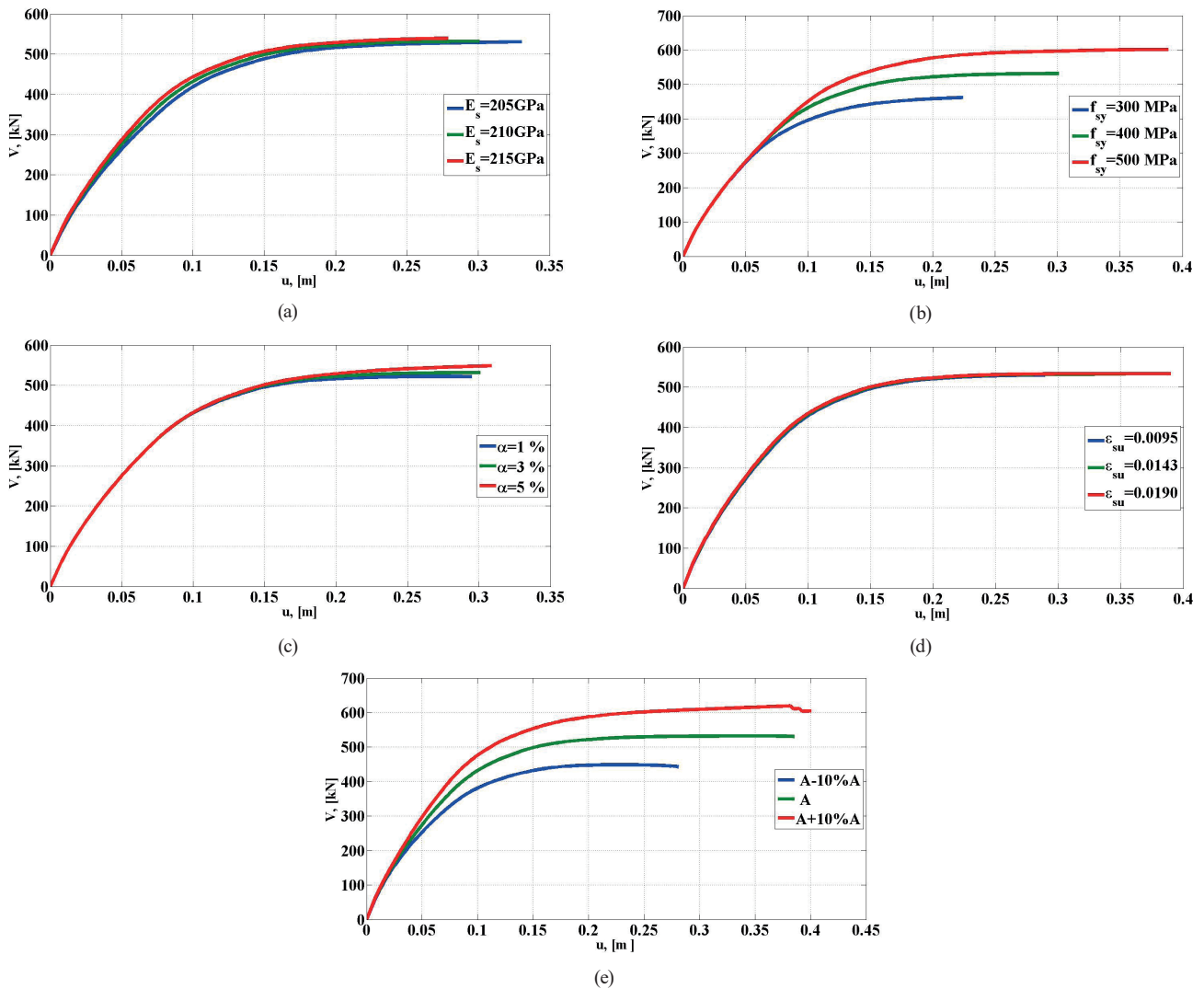
Fig. 5 Influence of the steel parameters of the structure on the Pushover curve; (a) modulus of elasticity of steel, (b) yield strengths for longitudinal reinforcement, (c) hardening of steel, (d) ultimate deformation of the steel and (e) amount of reinforcement
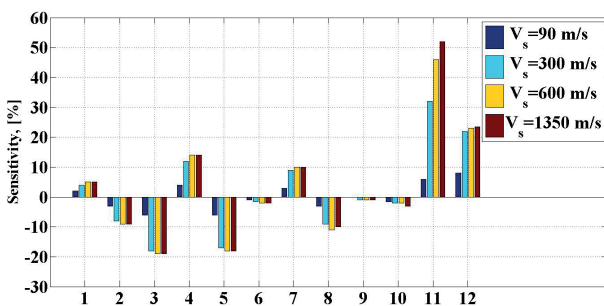

Fig. 6 Sensitivity of the main parameters of the three models: confined concrete, unconfined concrete, and steel for a value of PGA = 0.1 g
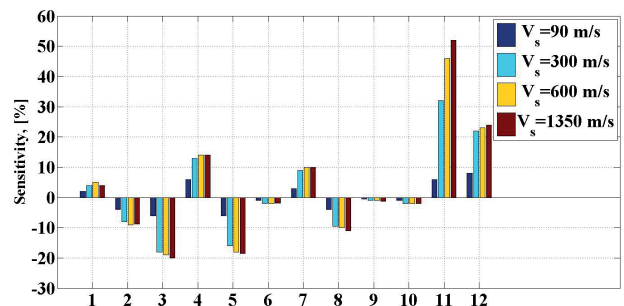

Fig. 7 Sensitivity of the main parameters of the three models: confined concrete, unconfined concrete, and steel for a value of PGA = 0.6 g

4.3 Influence of the concrete parameters of the structure on the Pushover curve – results

Confinement generally increases two characteristics of concrete: the compressive strength $f_{cc} > f_{c0}$ and the strain corresponding to the ultimate compressive stress $\varepsilon_{cc} > \varepsilon_{c0}$;

it also significantly increases the energy absorbing capacity of concrete. Thus, confinement has a favorable influence on the performance of concrete provided by transverse reinforcement. This is observed in Fig. 4, which shows that the sensitivity to unconfined concrete parameters is greater

than that to confined concrete parameters. Outside the area bounded by the transverse steel, the concrete has different stress-strain characteristics than the concrete inside the core. The embedding concrete generally begins to detach when the strength of the unconfined concrete is reached.

The study of the effect of concrete compressive strength on the strength and deformation capacity of the structures was carried out considering three values of concrete compressive stress: (20, 25 and 30 MPa for confined concrete and 25, 30 and 40 MPa for unconfined concrete). The analysis in Fig. 4(a) shows that the stiffness and shear strength of the structure increases significantly with f_{cb}.

The results obtained for different values of the peak strain ε_{c0} corresponding to the compressive strength of concrete show that the shear force at the base of the structure increases with the increase of ε_{c0} for displacements less than 20 cm, and then remains equal beyond this displacement, see Fig. 4(b). Therefore, the initial stiffness of the structure is significantly affected by the variation of ε_{c0}.

In Fig. 4(c) (to the left) we observe a very weak influence of the ultimate deformation of the confined concrete, while in Fig. 4(c) (to the right) no distinction is visible between the three curves until the value of 0.17 m where the curves separate showing the effect of the ultimate deformation of the unconfined concrete.

4.4 Influence of the steel parameters of the structure on the Pushover curve – results

In Fig. 5(a), we see that the variation in the modulus of elasticity of steel has no influence on the overall elastic stiffness of the structure, or its ultimate shear strength. Figs. 6 and 7 show a sensitivity in neighborhood of 9% for rock, hard and soft soil and 3% for very soft soil, these properties being observed for both values of PGA.

The ultimate deformation capacity and strength of a structure is strongly influenced by the value of the yield strengths for longitudinal reinforcement. Increasing this parameter improves the resistance of the structure to shear as well as its displacement, as clearly shown in Fig. 5(b).

Hardening is a mechanical treatment that generates plastic deformations due to exceeding the elastic limit of steel. As shown in Fig. 5(c), choosing a higher value for strain hardening increases the resistance capacity of the structure for displacements greater than 15 cm. On the other hand, the maximum displacement calculated for different values of shear rate and PGA (0.1 g and 0.6 g) is not very sensitive to the increase in hardening (about 2%), see Figs. 6 and 7.

Figs. 5(d), 6 and 7, show that for a strong variation of the parameter ε_{su}, the sensitivity of the maximum displacement and the ultimate resistance of the structure to shearing remains very low. But it should be noted that this parameter can have a strong influence on the ultimate displacement of the structure. This displacement depends on the length of the plastic ball joint and the ultimate curvature. Indeed, horizontal solicitations cause plastic hinges to appear at the ends of structural elements due to the crushing of the concrete, in particular the loss of confinement and the rupture of longitudinal steels, when they reach their limit deformation ε_{su}. This parameter can have a considerable influence on the overall stability of the structure.

Three values were considered to demonstrate the effect of the amount of longitudinal reinforcement of columns and beams on the lateral deformations of the structure. The rate of change in the amount of reinforcement is 10%. The force-displacement curves obtained from the fixed base structure clearly show the increase in resistance with the increase in the amount of longitudinal steel in the columns (Fig. 5(e)).

A high longitudinal steel rate contributes to increasing the ultimate displacement of the structure. However, the maximum displacement of the structure decreases for the two types of soil: rock soil of V_s = 1350 m/s and very soft soil of V_s = 90 m/s. This is explained by the improvement in displacement ductility with the increase in the amount of longitudinal steel regardless of the nature of the soil.

4.5 Sensitivity analysis of the parameters relating to the materials of the structure - synthesis

The graphs presented in Figs. 6 and 7 summarize the information obtained for the sensitivity values, for each of the parameters studied and for the four types of soil. It is recalled that the sensitivity study relates to the maximum displacement of the structure for two earthquakes: weak of 0.1 g and strong of 0.6 g. Because the maximum displacement of the structure is a key element in the design especially by introducing the effect of the ground to know how the interaction between the ground and the structure with nonlinear behavior can modify the seismic demand and the capacity in the superstructure.

The parameters concerned by this study are independent, therefore the approach does not take into account either their potential correlation (two increase at the same time or one increases when the other decreases) nor of the fact that they can have coupled influences.

The most immediate result is that the structural response is very sensitive to the concrete and steel parameters as the shear wave velocity increases.

Modifying the data set inputs produces changes ranging from 0 to 52% in the output represented by the maximum displacement of the structure. A, ξ, ε_{cu}, and f_c' are the parameters which most influence this output (Figs. 6 and 7). They induce respective variations of 52, 24, 20, 16 and 14%. This analysis shows that rather large uncertainties on these parameters can greatly distort the results obtained for the output (maximum displacement of the structure). The figures also show a sensitivity in neighborhood of 22% for rock, hard and soft soil and 8.5% for very soft soil and that for the two values of PGA.

In the end, if we use a threshold of 20%, three parameters seem very influential: the rate of reinforcement, the damping of the structure and the ultimate deformation of the confined concrete.

4.6 Sensitivity analysis of soil parameters

The results obtained in the previous section clearly show that the sensitivity of the parameters of concrete and steel on the response of the structure increases jointly with the increase in the value of the speed of the shear waves (case of a rock soil). In order to evaluate the contribution of soil parameters such as: soil damping ξ_g and Poisson's ratio v (Table 3) on the maximum displacement of the structure in interaction with the soil, a sensitivity analysis on these parameters was made for four types of soil (Fig. 8).

The damping of the soil and the Poisson's ratio in the case of a soil with $V_s = 90$ m/s, constitute the main inputs having the greatest influence on the output which represents the maximum displacement. For the two inputs, the displacement has sensitivity indices ranging from 16 to 39.9. On the other hand, these two parameters are not very sensitive to the variability of the seismic response in interaction for the rock soil. This analysis shows that quite large variations on these two parameters in the case of a structure based on very soft soil can greatly distort the results obtained for the seismic response of a structure. The influence of the parameters (ξ_g and v) remains
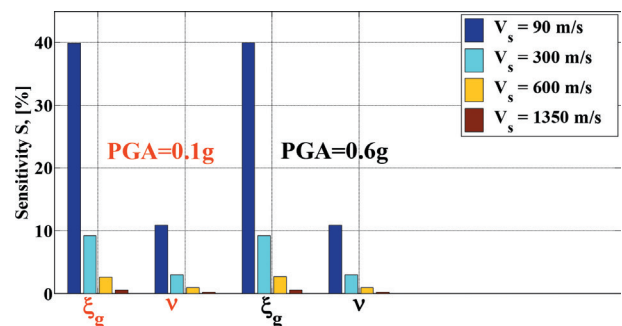
marginal in the case of a structure based on rock soil, so we can ignore the uncertainties associated with them and consider them as deterministic in this case.

The sensitivity study conducted in this section has highlighted the importance of the use of random models in the study of interacting systems. However, to arrive at reliable estimates of the response of the structure in interaction with the ground it is necessary to resort to reliable methods for the determination of the values of the shear wave velocity V_s.

The results obtained following this study show that the proposed model is greatly influenced by the variation of the three parameters: the soil, the structure, and the earthquake. Among these parameters, it was found that the soil parameters and more precisely the shear wave velocity V_s introduces a great deal of uncertainty on the estimation of the overall damping of the soil structure system and therefore on the displacement of the structure.

5 Effects of uncertainties of correlated parameters V_s and ξ_g on the maximum displacement of the SSI

In many geotechnical uncertainty analyses, it is not easy to obtain accurate and complete correlation relationships of different random variables because of the lack of knowledge and data. For those reasons, the correlation between input data is often neglected. If this correlation has an influence on the system response, the lack of knowledge of the epistemic uncertainties due to this correlation can be a risk factor. To our knowledge, no studies take into account the variability of correlated parameters (positive, negative or zero) between shear wave velocity V_s and soil damping ξ_g on the seismic response of soil-structure interaction systems. In this context, we study the influence of the correlation between these random variables of the model. This possible relationship has an impact on the probability of simulated failure as well as on the sensitivity analysis. For this reason, the influence of the

Table 3 Soil parameters and their maximum and minimum variations

Materials	$(X)^-$	$(X)_{Ref}$	$(X)^+$	$(\partial X/X)^-$ en %	$(\partial X/X)^+$ en %
Soil damping, ξ_a [%]	5	10	15	-50.00	+50.00
Poisson coefficient, v	0.2	0.3	0.4	-33.33	+33.33

Fig. 8 Sensitivity of soil parameters for two values of PGA (0.1 and 0.6 g)

correlation between these two variables was considered for three values -0.5, 0 and +0.5, and the other parameters were assumed as independent of each other. The correlation was assumed to be linear.

To analyze the variability of the two correlated parameters V_s and ξ_g, a numerical simulation was carried out for four different average values of shear wave velocity (very soft soil (with a shear wave velocity of 90 m/s), soft soil (V_s = 300 m/s), hard soil (V_s = 600 m/s), and rock soil (V_s = 1350 m/s)) and an average value of ξ_g = 10%. Two coefficients of variation CoV were used according to the two configurations represented in Table 4. All other data relating to the concrete and steel properties used in this application are reference data mentioned in the Table 1.

An example of the influence of the correlation coefficient between two variables V_s and ξ_g is shown in Fig. 9, where 100,000 samples of a random variable of V_s and similarly for ξ_g were chosen for three correlation coefficients (-0.5, 0 and 0.5). We note that the link between the two variables increases with the absolute value of the correlation coefficient (correlation coefficient = -0.5 and 0.5). When the latter is equal to 0, the two variables become independent.

The Figs. 10 and 11 shows the ratios distribution functions of the SSI top displacements system considered fixed at its base ($\tilde{u}_t/u_t$) for the cases 1 and 2, respectively. These figures are obtained for three correlation coefficients ($\rho_{V_s\_\xi g}$ = −0.5, 0 and + 0.5) and for four soil types (rock, hard, soft, and very soft). The figures clearly show that the variability of the maximum displacement differs from one soil to another; the cumulative probability curves become more and more spread out going from rock soil to very soft soil for the two cases.

As expected, the ratio $\tilde{u}_t/u_t$ approaches unity for larger values of V_s. For V_s = 90 m/s and for the two cases, the Figs. 10 and 11 shows an increase in $\tilde{u}_t/u_t$. For example, for
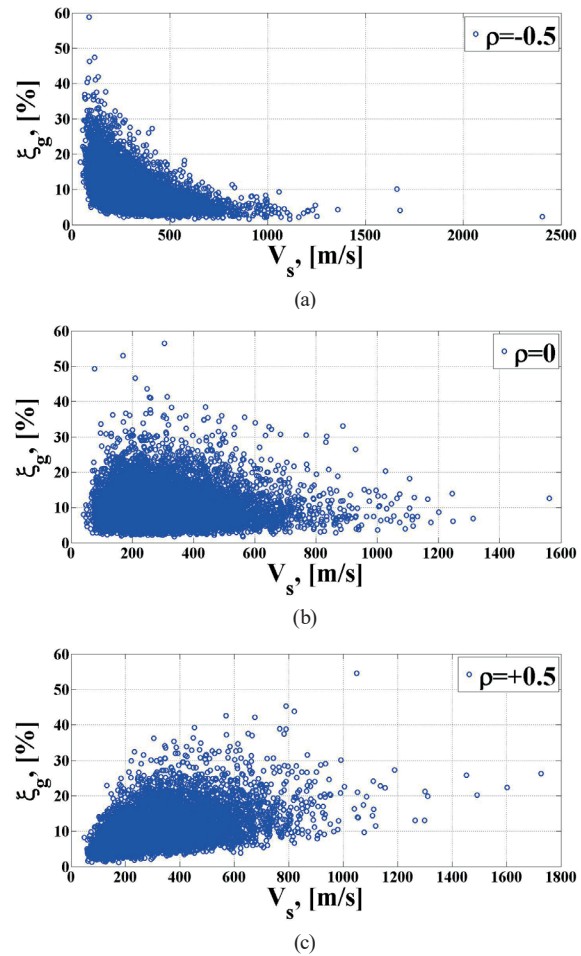

Fig. 9 Representation of the correlation between V_s and ξ_α for hard soil (case 2)

case 1, the top displacement average is 1.4 times greater than in the fixed base case. This is mainly due to the increased damping of the system with the increasing of SSI effects.

In the case where the coefficient of variation of V_s and ξ_g = 10% for the four soil types (Fig. 10), a very low variability of the maximum displacements ratios $\tilde{u}_t/u_t$ is observed (for example, between 1.1 and 1.8 for very soft soil (Fig. 10). This variability begins to expand for the four soil types when the CoV of V_s and ξ_g = 50% (Fig. 11) (For example the top displacement of the fixed base soil-structure system is variable between 0.6 and 4.0).

The main design codes (e.g., [38, 39]) consider the introduction of the SSI into the dynamics analysis is beneficial. However, for other authors, the SSI effects can be detrimental [16] and can amplify the structural response compared to a fixed-base model. Our case study confirms this last conclusion. For example, for a CoV of V_s of 10% and a CoV of ξ_g of 10% and for four soil types (rock, hard, soft and very soft), the top displacements average of the fixed base soil-structure system are, respectively: 1.00, 1.01, 1.04

Table 4 Variability of soil parameters (V_s and ξ_α)

Cases	Uncertainty parameters		Distribution	Mean	CoV
Case 1	ξ_α [%]		Log-normal	10	0.10
	V_s, [m/s]	Rock	Log-normal	1350	0.10
		Hard	Log-normal	600	0.10
		Soft	Log-normal	300	0.10
		Very soft	Log-normal	90	0.10
Case 2	ξ_α [%]		Log-normal	10	0.50
	V_s, [m/s]	Rock	Log-normal	1350	0.50
		Hard	Log-normal	600	0.50
		Soft	Log-normal	300	0.50
		Very soft	Log-normal	90	0.50

Fig. 10 Effect of correlation coefficient between V_s and ξ_α on the distribution functions of the ratio $(\tilde{u}_t/u_t)$ for 4 types of soil (case 1)
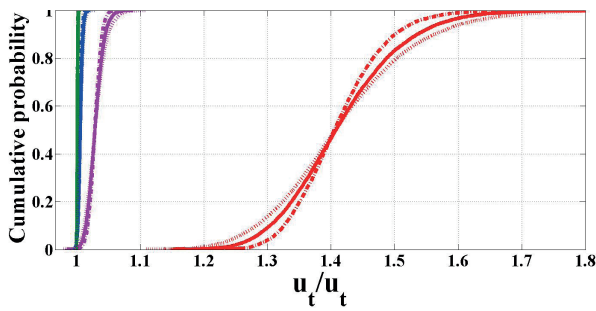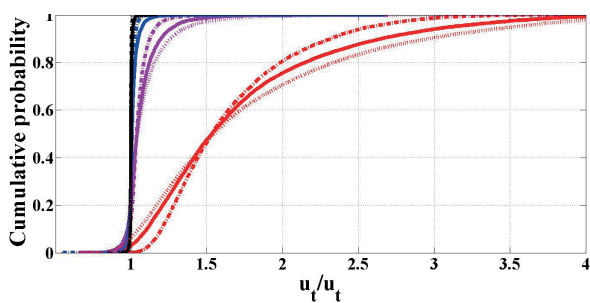$(-\cdot-\cdot\ \rho = -0.5, \ —\ \rho = 0, \ \cdots\cdots\ \rho = +0.5)$

Fig. 11 Effect of correlation coefficient between V_s and ξ_α on the distribution functions of the ratio $(\tilde{u}_t/u_t)$ for 4 types of soil (case 2)
$(-\cdot-\cdot\ \rho = -0.5, \ —\ \rho = 0, \ \cdots\cdots\ \rho = +0.5)$

and 1.40. Thus, we clearly see the detrimental SSI effect.

It can be noted that for larger values of the variation coefficient, either for V_s or for ξ_g, a change in the correlation coefficient $\rho_{Vs\_\xi g}$ can significantly affect the SSI response distribution. Fig. 11 (Case 2) confirm this observation.

It can also be noted that the ratio $\tilde{u}_t/u_t$ is not very sensitive to the variability of the correlation coefficient $\rho_{Vs\_\xi g}$ when the variation coefficients of the two parameters (V_s and ξ_g) are small. This means that the determination of the structural response can be obtained without considering the dependence or independence of the variables on each other if one seeks only to estimate the median response.

6 Conclusions

In this article, a sensitivity study was conducted to investigate the influence of deterministic variables on the structural response. The objective of this analysis is to study the impact of the parameter variations on the model. This analysis provides a better understanding of the uncertainties associated to these parameters in a satisfactory manner. However, a better knowledge of the model uncertainty helps to improve the accuracy of the models and, also a better understanding of the relationships between the model assumptions, the parameters, the data, and the predictions of the model.

The seismic behavior of a reinforced concrete structure has been studied taking into account the SSI and the nonlinear behavior of the structure. An approach has been proposed (N2-SSI) and developed. It can be applied to practically to any type of regular RC structure and for a given geotechnical environment. The approach is based on an extension of the N2 method by determining the capacity curve of the fixed base system oscillating mainly in the first mode, then modified to obtain the capacity curve of the flexible base system using the concept of 1 equivalent nonlinear oscillator.

The sensitivity analysis carried out on the maximum displacement of the structure by varying the characteristics of the materials showed that this displacement is very sensitive to the concrete and steel parameters when the shear wave velocity increases.

The results from this sensitivity analysis have shown that the displacement of the structure is visibly sensitive to the parameters A, ξ, ε_{cu}, ε_{c0} and f_c'. They induce variations of 52, 24, 20, 16 and 14%, respectively. These results lead us to conclude that rather large uncertainties on the aforementioned parameters can lead to distort the estimate of the maximum displacement of the structure. The analysis also showed a sensitivity in neighborhood of 22% for rock, hard and soft soil and 8.5% for very soft soil and that for the two values of PGA (0.1 and 0.6 g).

Concerning the sensitivity of the maximum displacement with respect to the parameters of the soil, the damping of the soil and the Poisson's ratio in the case of a very soft soil ($V_s = 90$ m/s) seem to be the main inputs having the greater influence on the output for these two inputs, the displacement has sensitivity indices ranging from 16 to 39.9. On the other hand, for a rock soil, these two parameters are not very sensitive to the variability of the seismic response in interaction. So quite large variations on these two parameters in the case of a structure based on very soft soil can greatly distort the results obtained for the seismic response of a structure. The influence of the parameters (V_s and ξ_g) remains marginal in the case of a structure based on rock soil, so we can ignore the uncertainties associated with them and consider them as deterministic in this case.

The results obtained show that for larger values of the coefficient of variation, either for V_s or for ξ_g, a change in the correlation coefficient $\rho_{Vs\_\xi g}$ can significantly affect the SSI response distribution. However, this response is not very sensitive to the correlation coefficient $\rho_{Vs\_\xi g}$ variability when the variation coefficients of the two parameters are low. This means that the determination of the structural

response can be determined without considering the dependence or the independence of the variables between them if one seeks only to estimate the median response.

The results obtained in this article concern only material prosperities and soils parameters variations for one type of structure and four different types of soils. However, we plan to extend this study to other types of structures with different heights and geometries as well as other types of foundation soil for a better understanding of the behavior of SSI systems.

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