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Geotechnical aspects that control the seismic response in structures designed according to code regulations

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ABSTRACT

In this paper the new seismic code regulations to consider the site effects and soil-structure interaction in Mexico are analyzed. Specifically it is referenced to the seismic design criteria established in the recently reviewed CFE Code for Civil Structures. The simplified models used in this code are presented and the main ideas for the formulated design criteria are exposed. With some results the improved changes in the design approach are showed, but the unresolved aspects are discussed too.

RESUMEN

En este trabajo se examinan las nuevas disposiciones de diseño sísmico en México para tener en cuenta los efectos de sitio e interacción suelo-estructura (ISE). Específicamente se hace referencia a los criterios de diseño por sismo del Manual de Diseño de Obras Civiles de la CFE recientemente revisado. Se describen los modelos simplificados usados para el análisis y se exponen los razonamientos que condujeron a la formulación de los criterios de diseño especificados. Con algunos resultados se ilustran las mejoras en el enfoque de diseño, pero también se discuten aspectos aún sin resolver.

1 INTRODUCTION

In the absence of a local seismic regulation, in our country the buildings are usually designed according to the CFE Seismic Design Code (MDS-CFE, 2010). Therefore it is worthwhile to review the new design criteria for each seismic event specified in this reviewed code in order to consider the site effects and the soil structure interaction (SSI). The first ones are related with the dynamic amplification of the ground movement due to the geotechnical characteristics of the site and the second ones with the modification of the movement of the foundation, in relation to the open field movement, due to the flexibility of the support ground.

The seismic hazard in Mexico has been re-evaluated and at the present time we can estimate the maximum acceleration on rock for any given point of the country using software developed for that purpose. This is the starting point for the construction of specific site design spectrum that explicitly includes the effects of the local conditions. This way the concept of seismic regionalization of the country disappears and also the regional spectra by type of ground. The effects of SSI can be grouped in two stages: First in the elastic design spectra, considering the enlargement of the period and the increase in damping; and then in the resistance reduction factor, taking into consideration the ductility reduction.

For seismic movements represented in elastic design spectra, the creep resistance is obtained by applying a reduction factor for ductility that correlates the resistance for the elastic condition and the required resistance for a given ductility. In the case of a non deforming support, this factor is calculated through the solution of an elastoplastic simple oscillator, but if the support is flexible, a replacement oscillator characterized by the period, damping and ductility of the system can be applied. Based on its definition, the reduction factor due to ductility with or without SSI should be applied to the specific elastic spectra.

In the conventional design view, open field spectra are used to evaluate the seismic actions on structures. However, in structures with basement stories it may not be representative of the foundation's true movement, since the incoming waves diffraction by the walls and cover of the foundation caisson has been neglected.

The criteria to construct floor spectra calculated with the true movement of the base, has not yet been specified. Some investigations directed clarify these aspects are now in process, so they can be included in future Code updates.

2 ELASTIC DESIGN SPECTRUM

At the moment it is clear that the seismic hazard varies significantly within the national territory and that cannot in detail be described by means of regional spectra for different types of land. In order to consider it more accurately it is necessary to construct specific site design spectra, which depend mainly on the proximity from the place to the tectonic sources and of the local conditions of the subsoil.

In the seismic behavior of structures, several factors intervene that have to do with the source, the wave's path, the site and the structure itself. In order to simplify the problem, a defined characteristic seism is adopted as design seism defined in conditions of firm ground, in such a way that the effects of source and wave's path are considered implicitly.

This way, it would be necessary to take into account the site effects and SSI to determine the structural response. In order to do this, a simplified model is used as the one shown in figure 1, formed by an equivalent strata and an elementary oscillator in representation of the subsoil and the fundamental vibration mode of the structure respectively. For the analyses described here, a site in the city of Puebla (UAPP - Independent University of Puebla) has been considered, with dominant period T_s = 1.25 s, effective speed V_s = 80 m/s, strata thickness of H_s = 25 m, Poisson's ratio ν_s = 0.4 and hysteretic damping ζ_s = 0.05. In all the cases a contrast of impedances $p_s = \rho_s\ V_s\ /\ \rho_o\ V_o$ = 0.2 was assumed between the ground and the basement, a slenderness ratio H_e/r = 5 for the structure and a relation of burying e/r = 1 for the foundation.

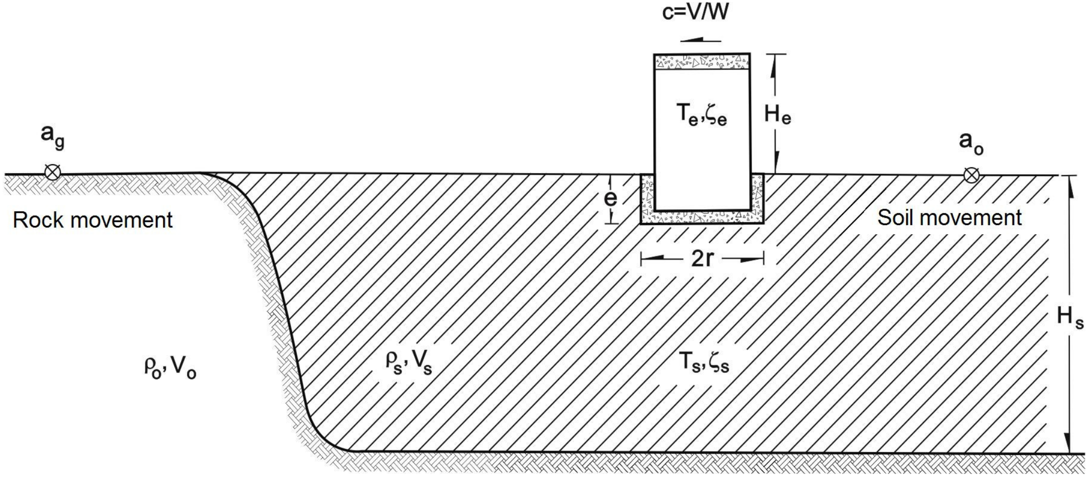

Figure 1. Reference simplified model to consider the site effects and the SSI

2.1 Site effects

The site effects amplify the ground acceleration, a_o in relation to firm ground .a_g It also amplifies the structural response ,a in relation to the base movement. The seismic hazard on rock is specified in the map of figure 2, supplying optimal values of a_g for the collapse limit stage of group B structures. These optimal coefficients correspond to different return periods, that vary in time from around 350 years for zones with high seismic activity to up to 10,000 years for zones with low seismic activity.

The parameter that controls the site effects is the dominant period of the ground. In order to calculate T_s it is necessary to perform local geotechnical studies and analyze the dynamics of the ground. Or apply a simplified criteria indicated in the MDS, based on the Rayleigh method and a static approximation for the fundamental mode of the ground. This is superior to the traditional criteria of averaging de strata speed that ignores the configuration of the ground.

In terms of period T_e and the structural damping ζ_e the site spectrum for the seismic design has the following form:

$$a=\frac{Sa}{g}=\begin{cases} a_o+[\beta c-a_o]\dfrac{T_e}{T_a}; & \text{si } T_e<T_a \\ \beta c; & \text{si } T_a\le T_e<T_b \\ \beta c\dfrac{T_b}{T_e}; & \text{si } T_b\le T_e<T_c \\ \beta c\dfrac{T_b}{T_c}\,p_c\left(\dfrac{T_c}{T_e}\right)^2; & \text{si } T_e\ge T_c \end{cases} \tag{1}$$

where $p_c = k + (1-k)(T_c / T_e)^2$, being $k = 2 - Ts \geq 0.35\ s$ the quotient between the maximum displacement of the ground and the structure. A difference with the traditional spectra, this can have two descendent branches and is dependent on various parameters that are function of T_s .

The physical meaning of each one of them, is described as follows.

a) For the lineal behavior of the ground, the maximum acceleration coefficient of the ground is calculated as

$$a_o = F_s\, a_g \tag{2}$$

Where a_g is the maximum acceleration in rock, obtained from the map of the site of interest in Figure 2.

The site's factor of response, F_s, measures the ratio of maximum accelerations on the surface and the outcrop. It was obtained analyzing the open field response, using as initial movement the entrance power spectrum for the design earthquake (Park, 1995) and applying the Random Vibrations Theory (Boore and Joyner, 1984).

The proposed values of F_s, are indicated in table1 for different values of the normalized period $T_s' = T_s F_d^{1/2}$ and the contrast impedances p_s; $F_d = a_g / 400 \leq 1$ is a parameter that considers the attenuation of the seismic waves with the distance and the filtering of high frequency components of the seism.

The theoretical results obtained compared with the ones that result from inserting the tabulated values of F_s are shown in Figure 3.

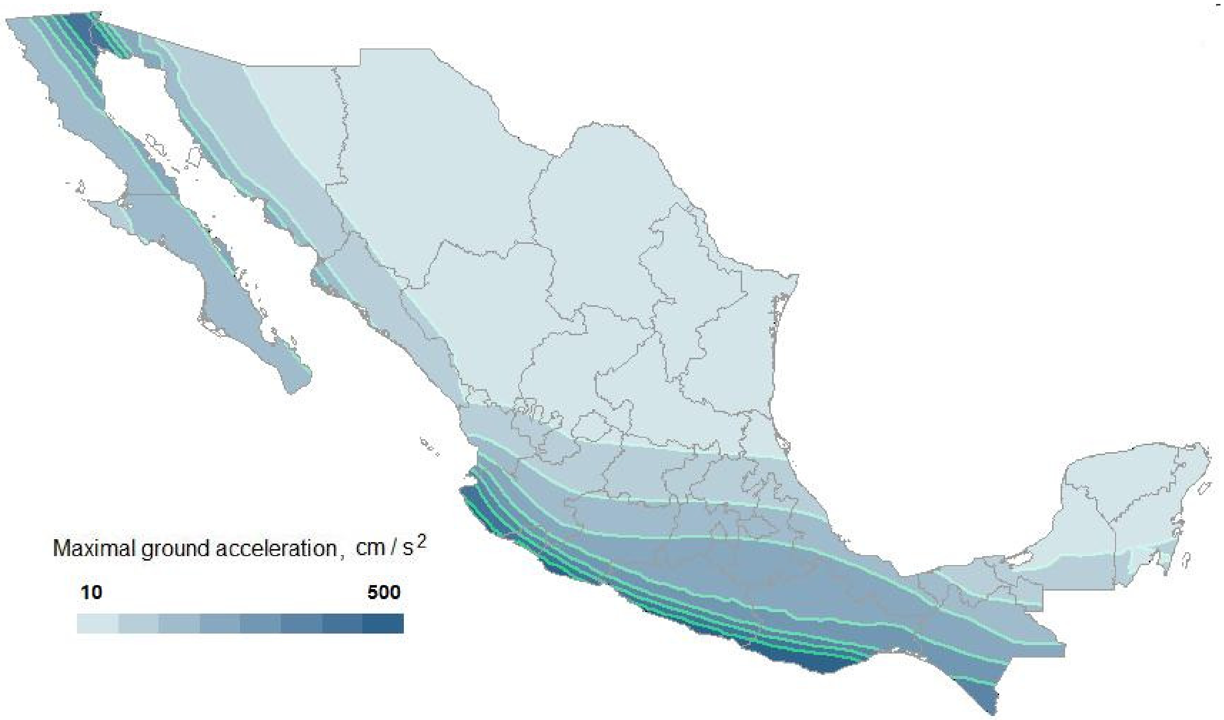

Figure 2. Distribution of the maximum acceleration en rock for group B structures

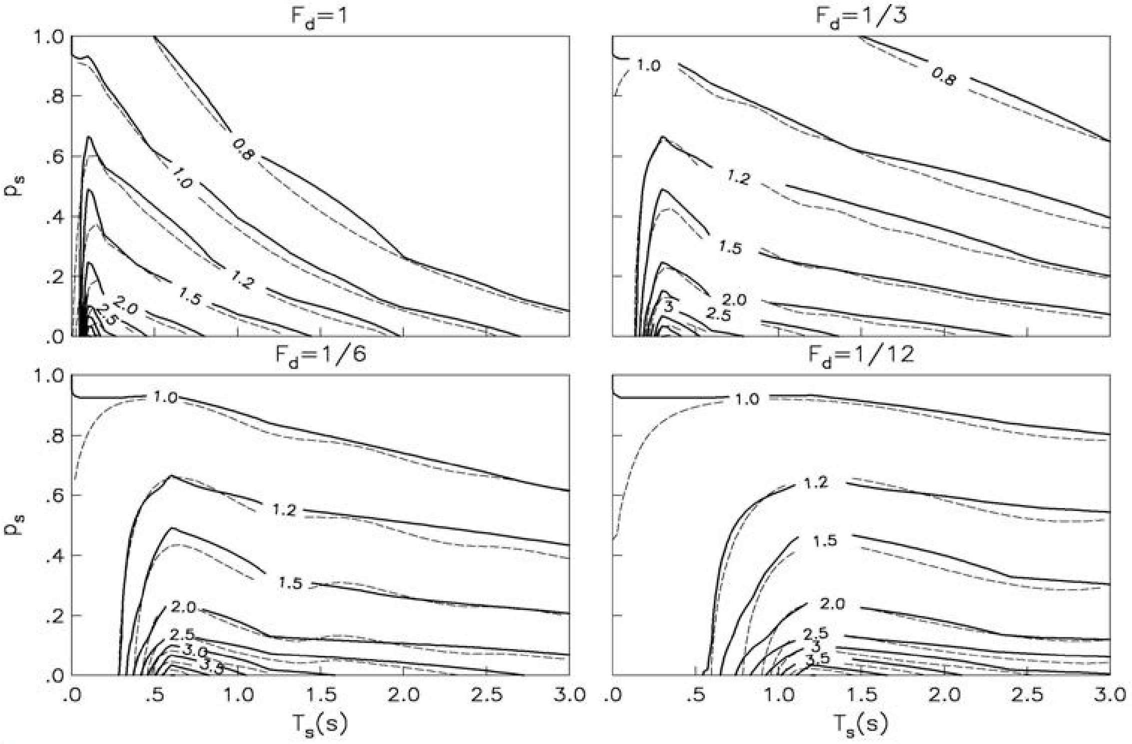

Figure 3. Contours of F_s factor obtained from the analysis of the response of open field (Non continuous line) and the insertion of data from table 1 (continuous line)

Table 1. Values of Factor F_s to consider the amplification of the site response

$T_s'(s)$ / p_s	0.00	0.05	0.10	0.20	0.50	1.00	2.00	3.00
1.000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.625	1.00	1.08	1.23	1.12	1.00	1.00	1.00	1.00
0.250	1.00	1.18	1.98	1.60	1.40	1.12	1.00	1.00
0.125	1.00	1.20	2.64	2.01	1.69	1.32	1.00	1.00
0.000	1.00	1.22	4.51	3.17	2.38	1.75	1.19	1.00

b) The seismic coefficient that represents the ordinates of the spectral plateau is calculated as follows

$$c = F_r\, a_o \tag{3}$$

Where the factor of structural response F_r measures the relation between maximum acceleration of the structure and the ground. It was obtained through the analysis of the random response of an oscillator stimulated by the open field movement. The proposed values of F_r are indicated in table 2 for different values of Ts and ps, supposing that F_d = 1 because the effect of the distance is small. The theoretical results obtained are shown in figure 4, compared with the results of randomly inserting the values of F_r tabulated.

Table 2. Values of Factor F_r to consider the amplification of the structural response

$T_s(s)$ / p_s	0.00	0.05	0.10	0.20	0.50	1.00	2.00	3.00
1.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
0.625	2.50	3.80	3.74	3.57	3.26	2.81	2.56	2.51
0.250	2.50	4.36	4.41	4.27	3.45	2.85	2.59	2.53
0.125	2.50	4.74	4.91	4.90	3.70	3.06	2.75	2.65
0.000	2.50	5.27	5.66	6.02	4.81	4.05	3.58	3.40

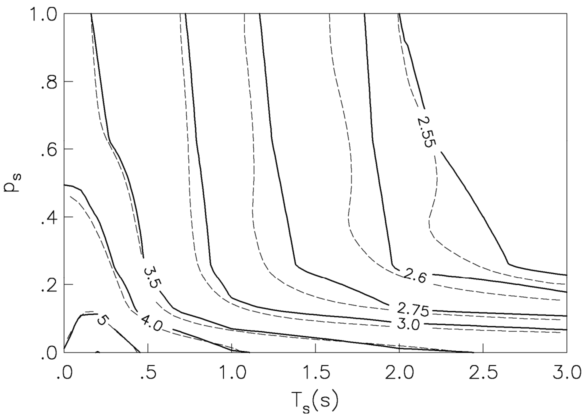

Figure 4. Contours of factor F_r, obtained by the analysis of the nonlinear response (non continuous line) and the random linear application of the data from table 2 (Continuous line)

c) The inferior limit (T_a) and the superior (T_b) limit of the spectral plateau are

$$T_a = 0.35 T_s \geq 0.1\, s \tag{4}$$

$$T_b = 1.2 T_s \geq 0.6\, s \tag{5}$$

The expressions of these characteristic periods try to cover the maximum response of the first and second modes of ground vibration, as well as the difference between the true and calculated values of T_s.

d) To guarantee that the long period spectral displacements tends to the maximum displacement of the ground, a second descendant ramification was introduced, which begins in

$$T_c = \begin{cases} 2\, s; & \text{if } T_b < 2\, s \\ T_b; & \text{if } T_b \geq 2\, s \end{cases} \tag{6}$$

Notice that when $T_c = T_b$ the first descendant ramification disappears, since it begins at T_b and finishes at T_c. In this case, the design spectrum of MDS-CFE (2010) adopt the form specified by the Mexico City Seismic Design Code (NTCDS-RCDF, 2004) for sites with soft ground.

e) In the specification of the design spectrum, equation 1, a viscous damping value of $\zeta_e = 0.05$ is implicit. To consider the supplementary damping effects of SSI or the use of energy dissipators, a reduction factor has been introduced

$$\beta = \left(\frac{0.05}{\zeta_e}\right)^{\lambda}, \text{ with } \lambda = \begin{cases} 0.45; & \text{if } T_e < T_c \\ 0.45\dfrac{T_c}{T_e}; & \text{if } T_e \geq T_c \end{cases} \P \tag{7}$$

This equation is based on the research results obtained by Rosenblueth and Reséndiz (1988) and Ruiz and Toxqui (2008) on the effects of damping in the spectral ordinates. Note that $\beta = 1$ for $\zeta_e = 0.05$ and that it tends to one for long period where the spectral ordinates are independent of the damping.

Figure 5 illustrates the shape that the design spectra take for ζ_e =5 and 10%. For the purpose of comparison, the response spectrum for the Tehuacán earthquake (15/VI/99) registered at the UAPP site and scaled to the ground's maximum acceleration specified by the codes, without modifying the frequency content or the duration of the ground motion.

2.2 Interaction effects

It is known that SSI modifies the relevant dynamic properties that a rigid base structure would have, as well as the characteristics of the open field movement around the foundation. The enlargement of the fundamental period and the increase in associated damping are due to an inertial interaction. By the other hand the cinematic interaction reduces de horizontal translations and generates rotation components. If this last point is ignored, the effects of SSI can be considered modifying the relevant dynamic properties of the original structure and analyzing the modified structure subject to the specified open soil movement.

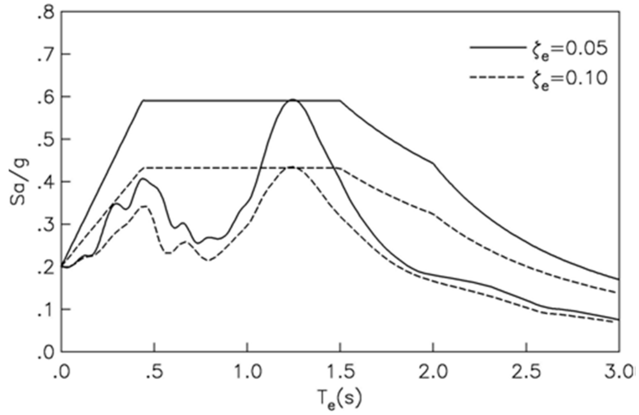

Figure 5. Effect of damping in the spectral response: design spectra versus response spectra.

The site effects and SSI are controlled by the site's period T_s and the effective velocity V_s, respectively; this last one measures the ground flexibility. Using the design spectrum, the interval and damping can take the values $\tilde{T}_e$ and ζ_e of the rigid base structure, or the values $\tilde{T}_e$ and $\tilde{\zeta}_e$ of the flexible base specified in the codes.

In figure 6 the design spectra obtained for the site study with and without SSI are shown, together with the elastic response spectra observed. In both cases, the protection of the design spectra is clearly satisfactory.

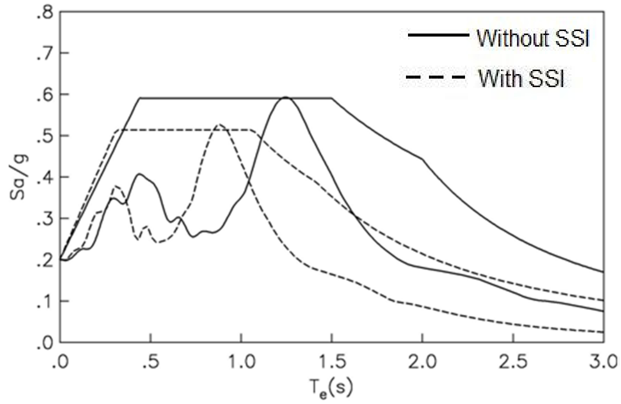

Figure 6. Effect of SSI in the spectral response: design spectra versus response spectra.

3 REDUCTIONS OF THE ELASTIC DESIGN SPECTRUM

The site spectra for seismic design is elastic, without any type of reduction. The equation 1 exclusively reflects the seismic hazard of the site in the spectral ordinates. To be reduced by ductility and over resistance in order to calculate the design resistance. In the code, the resistance reduction factor is defined as the product of $Q'_e R_s$, were Q'_e, is the reduction factor for ductility and R_s, is the reduction factor for over resistance. Because of it's nature, this last factor does not depend on the site effects nor SSI, therefore not worthy of a greater comment.

3.1 Replacement oscillator

To evaluate resistance reduction by ductility, the response of a elastoplastic simple oscillator is used. Such an option can be adapted for the consideration of the SSI effects, using a replacement oscillator. This concept is schematically illustrated in figure 7.

The traditional procedures (Jennings and Bielak, 1973; Veletsos and Meek, 1974) to represent the flexible base structure by an equivalent rigid base oscillator does not take into account the structural ductility capacity. Nevertheless, they have been adapted by various codes in the world for its simplicity.

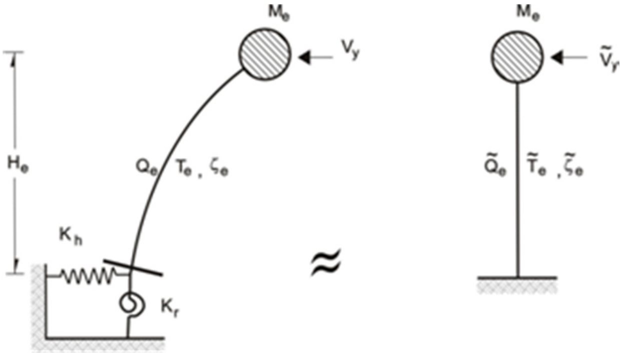

Figure 7. Representation of a flexible base structure through a replacement oscillator

Recently, it has been demonstrated (Avilés and Pérez-Rocha, 2005) that the flexible base structure can be substituted by a rigid base oscillator characterized by the interval $\tilde{T}_e$, damping $\tilde{\zeta}_e$ and ductility $\tilde{Q}_e$ of the system.

So that the replacement oscillator has the same resistance of fluency and capacity of plastic deformation that the original structure, see Figure 8, it requires that

$$\tilde{T}_e = T_e\sqrt{1+\frac{K_e}{K_h}\left(1+H_e^2\frac{K_h}{K_r}\right)} \tag{8}$$

$$\tilde{Q}_e = 1+(Q_e-1)\frac{T_e^2}{\tilde{T}_e^2} \tag{9}$$

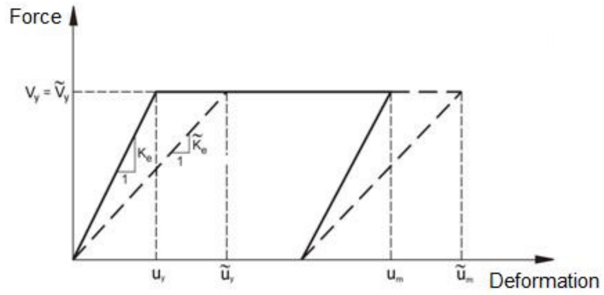

Figure 8. Resistance diagrams for the original structure (continuous line) and the replacement oscillator (non continuous line)

It is easy to see that the period of the system is enlarged in regards to the period of the rigid base, therefore the ductility of the system is reduced with regards to the available ductility of the original structure, as it is illustrated in Figures 9 and 10, respectively. It must be made clear that the reduction of the ductility of Q_e to $\tilde{Q}_e$ is due to a reduction of the rigidity of K_e to $\tilde{K}_e = (T_e/\tilde{T}_e)^2 K_e$. This additional flexibility reduces the design ductility factor, but not the capacity of structural ductility that remains unchanged.

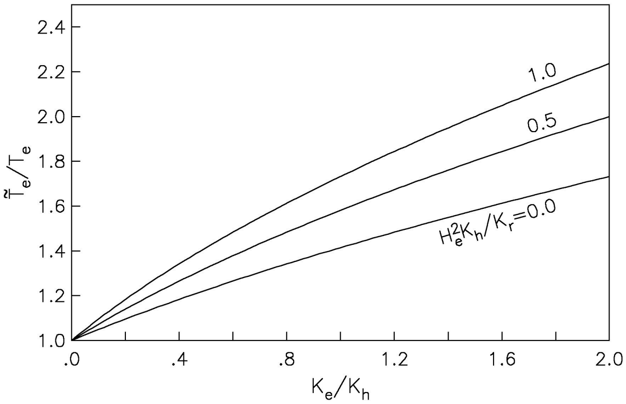

Figure 9. Effects of SSI in the system period

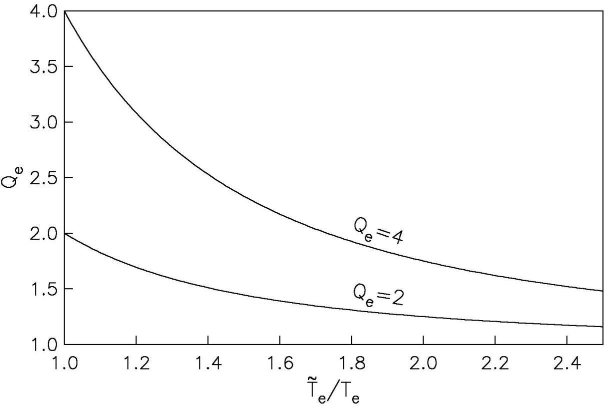

Figure 10. Effects of SSI on the ductility of the system

It must be said that that the relation between maximum displacement of the original structure and the replacement oscillator is given by:

$$u_e = \frac{T_e^2}{\tilde{T}_e^2}\frac{Q_e}{\tilde{Q}_e}\tilde{u}_e \tag{10}$$

This is due to the displacement of the replacement oscillator that includes the displacement of the structure as well as the movement contribution of the foundation as a rigid body.

It is important to point out that the parameters of SSI can be reduced to only one: the foundation flexibility coefficient.

$$\varphi = \frac{K_e}{K_h}\left(1 + H_e^2\frac{K_h}{K_r}\right) \tag{11}$$

In terms of this parameter, the quotient between the system periods and the structure ones is expressed as:

$$\frac{\tilde{T}_e}{T_e} = \sqrt{1+\varphi} \tag{12}$$

For a stiffness contrast $H_e/T_eV_s = 1/3$ between structure and ground, it has been found that $\varphi \approx 1$ if $H_e/r = 5$ and $e/r = 1$. Figure 11 shows the resistance spectra with and without the effects of SSI, using as ground motion a scaled accelerogram from the UAPP site. For $Q_e = 1$ and 4, a plot from the base line shear coefficients $C_y = V_y / M_e g$ (elementary oscillator) and $\tilde{C}_y = \tilde{V}_y / M_e g$ (replacement oscillator) is made.

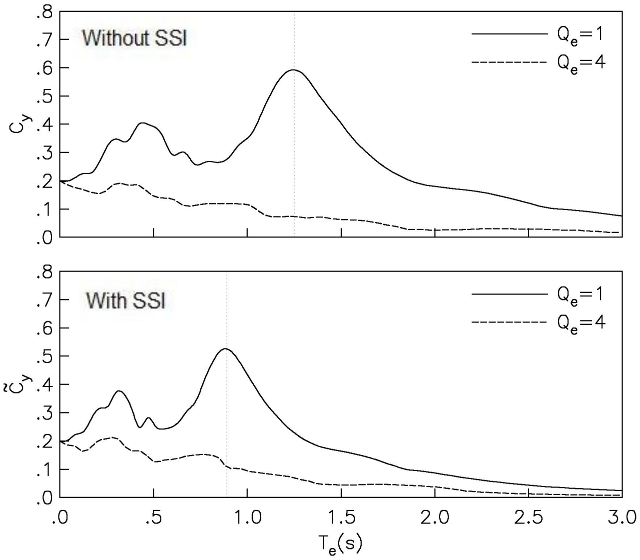

Figure 11. Resistance spectra with and without the effects of SSI, for elastic and non elastic conditions

3.2 Reduction for ductility

The determination of $Q'_e = C_y(1)/C_y(Q_e)$ allows the calculation of the non elastic resistance by the reduction of the elastic resistance. For structures on firm ground, the most accepted rule of ductility reduction is the design proposed by Veletsos and Newmark (1960). It is based on the premise that the maximum elastic and non elastic displacements are equal for moderate and long vibration periods. Empirical rules have also been developed by Miranda (1993) as well as Ordaz and Pérez-Rocha (1998) that take into account the site effects. These authors have shown that the resistance reductions on soft soils can be appreciably greater than those predicted by the rule equal displacement.

The reduction factor for ductility depends not only of Q_e, but also of T_e and ζ_e To calculate it, the following expression has been proposed:

$$Q'_e = \begin{cases} 1+(Q_e-1)\sqrt{\dfrac{\beta(1+\varphi)}{k'}}\,\dfrac{T_e}{T_b}; & \text{si } T_e \le T_b \\[2ex] 1+(Q_e-1)\sqrt{\dfrac{\beta(1+\varphi)\,p_b}{k'}}; & \text{si } T_e > T_b \end{cases} \tag{13}$$

Where $p_b = k' + (1-k')(T_b/T_e)^2$ being $k' = (2/3)k$ $\varphi = 0$ when SSI is ignored.

With this rule, the values of Q'_e for structural intervals around the site interval are greater than Q_e as it is shown en Figure 12, where there are also included the deducted values from the results of Figure11 without the effects of SSI.

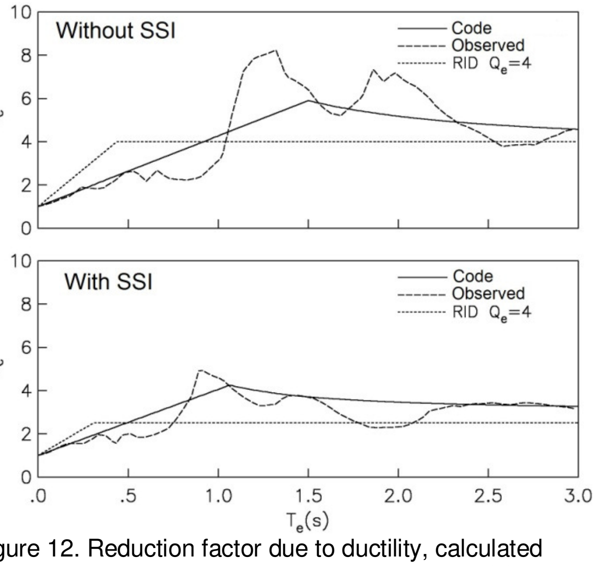

Figure 12. Reduction factor due to ductility, calculated versus observed, with and without the effects of SSI. As a reference the equal displacement rule is included.

In order to consider de effects of SSI in the reduction factor due to ductility, in the equation 13,the structure with a rigid base parameters T_e, ζ_e y Q_e are replaced by the flexible base structure parameters $\tilde{T}_e$, $\tilde{\zeta}_e$ y $\tilde{Q}_e$. Doing this we arrive to the $\tilde{Q}'_e$ values shown in figure 12, together with the deducted results of Figure 11 with the effects of SSI. Notice that the site effects, reflected around the site interval where $Q'_e > Q_e$, are offset by the effects of SSI. The reason for this is that the period of the structure moves towards the long interval spectral region, where the equal displacement rule applies.

In figure 13 the elastic design spectra found in figure 6 are shown, reduced by ductility with the factors shown on figure 12. There are also included the corresponding non elastic response spectra using as a source of ground motion a scaled accelerogram of the UAPP site. As we can see, the softened enveloping spectra, with and without the effects of SSI are satisfactory for the purpose of design.

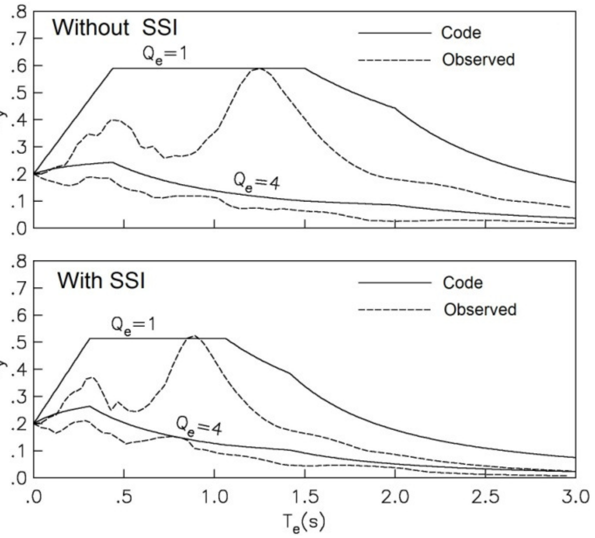

Figure 13. Design spectra reduced by ductility versus the non elastic response spectra observed, with and without the effects of SSI

4 FINAL REMARKS

We have reviewed the new seismic design criteria of the CFE Civil Works Design Manual to consider the site effects and the SSI. Such criteria are based on simplified models that idealize the structure as a simple oscillator and the ground as a homogeneous stratum over an elastic semi space. The site effects are considered through the construction of specific site design spectra. These spectra can be modified to consider the effects of SSI.

The criteria to consider the effect of the seismic waves on structures with several basement stories have not yet been specified. This can greatly affect the motion at the base and generate important seismic forces due to the deformation imposed by the ground movement.

Regarding the ductility reduction of the design spectrum, it was demonstrated that a practical rule proposed for rigid base structures can be adapted for structures with a flexible base, using the solution of a replacement oscillator. The results obtained by using the new code seem to be adequate for structures with a superficial foundation. However it is necessary to consider, in future revisions of the Code, the effect of seismic waves in deep foundations.

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