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SOIL-STRUCTURE INTERACTION EFFECTS IN TWO INSTRUMENTED TALL BUILDINGS

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SUMMARY

To estimate soil-structure interaction (SSI) effects in two instrumented buildings different models are explored. Both system identification and analytical methods are used to calculate stiffnesses and frequencies associated with SSI effects. The later include procedures from the Mexico City building code as well as commercial software by mean of which piles group effects are also considered. Experimental data from two of the most significant and recent earthquakes recorded in the buildings are analyzed and comparisons suggest interesting conclusions about analytical considerations and actual behavior of the buildings and theirs foundations.

INTRODUCTION

Today there are about 25 seismically-instrumented buildings in Mexico, from them, the two best instrumented were selected for this paper. The first one is located in Mexico City (JAL building) and the second one in Acapulco (SIS building). Both of them are founded on soft soil (figure 1) with dominant site frequencies about 0.5 and 0.75 Hz, respectively.

The JAL building is a 14-storey reinforced concrete structure and was one of the buildings that were damaged during the September 19, 1985 Michoacán earthquake. It has been twice retrofitted. SIS building is a 17-storey reinforced concrete structure built in 2000 and has not suffered any visual damage. Foundations of both buildings consist of embedded box supported by friction piles. Base dimensions are 40 m in the longitudinal (L) component and 20 m in transverse (T) component for the JAL building, and 32.9 and 37.5 m for the SIS building in L and T, respectively (figure 1).

Seismic instrumentation of JAL building started in 1992. During these twelve years of continuous monitoring most of the events recorded have been small and moderate intensity earthquakes. Nevertheless, the study of its response has revealed deterioration of the structural system, Murià-Vila *et al*. [1]. It is instrumented with 11 triaxial accelerometers strategically located along the structure besides a

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set of two deep-hole and free-field triaxial instruments. SIS building has 21 uniaxial well distributed accelerometers and a triaxial free-field instrument. Detailed information and other characteristics for JAL building could be found in Murià-Vila *et al*. [1], and for the SIS Building in Taborda [2] and Alcántara *et al*. [3].

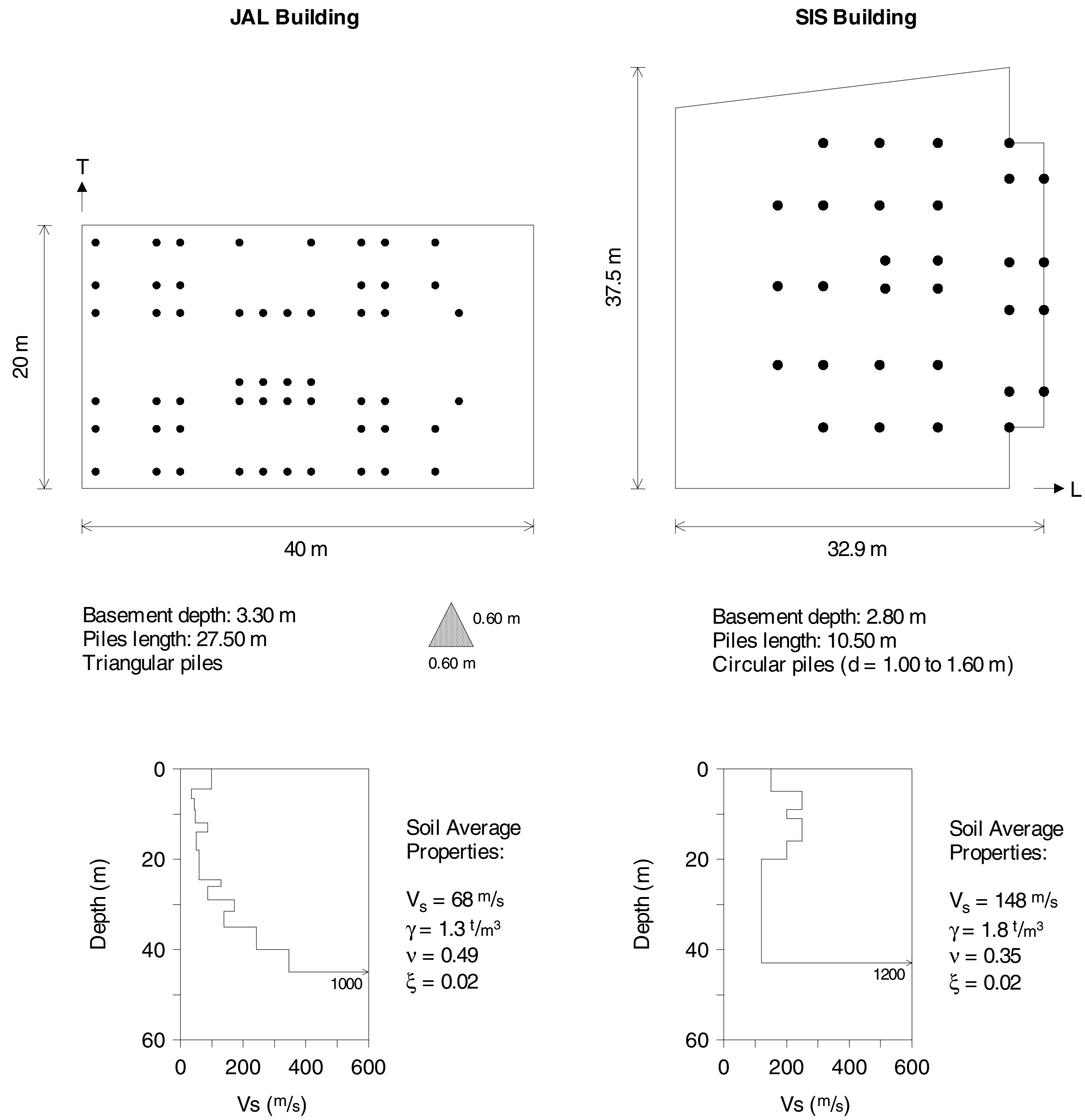

Figure 1. JAL and SIS building foundation plants and relevant soil properties

ANALYTICAL ESTIMATION OF SSI EFFECTS

Once foundation and soil properties from both buildings are known, it is possible to estimate, by means of analytical procedures, the translation (K_T and K_L) and rocking (K_{rT} and K_{rL}) stiffnesses associated with SSI effects. For this purpose Mexico City Building Code (RCDF) [4] and the commercial software Dyna5 [5] were used.

One source of SSI effects is the presence of the foundation itself. That is, the presence of piles as well as both piles and box as a whole system. According to RCDF, when considering that both of them are contributing to the foundation, SSI associated stiffness may be estimated as a direct sum of each piles and box stiffnesses evaluated separately. Following this consideration, two simple models were prepared for each analytical method used. An illustrative scheme of these models is presented in figure 2. It should be noted that, in the case of the piles group model, RCDF procedure does not allow defining the stratum profile as Dyna5 does, then average properties shown in figure 1 were used in this case.

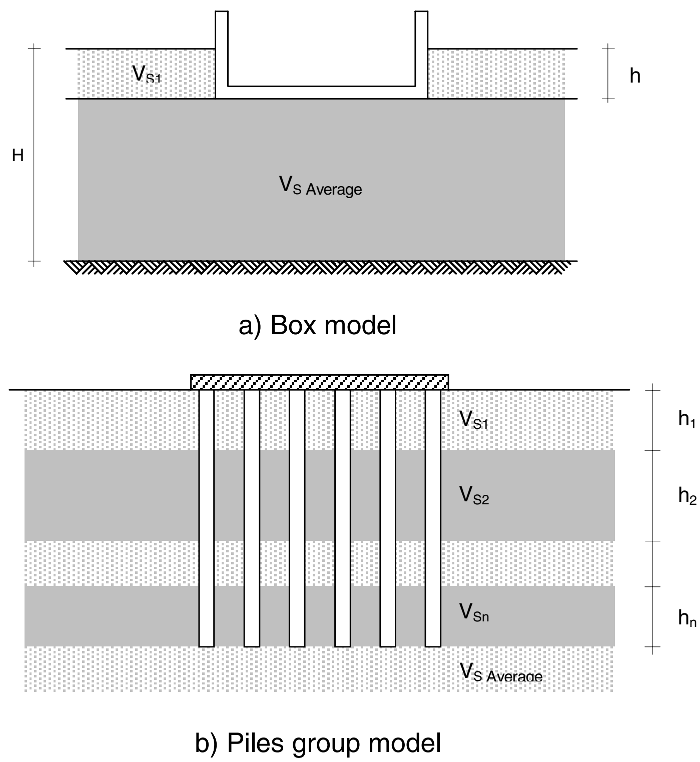

Figure 2. Basic models for assessment of foundation stiffnesses

An important consideration in estimating the foundation stiffnesses is whether including or not the piles-soil-piles and piles-soil-box group effects due to interaction between all foundation components, Novak [6]. It is known that piles-soil-piles group effect, which will be referred only as piles group effect, not only varies with pile diameters and spacing, and soil characteristics, but is also a frequency dependent factor that has an important consequence in final stiffness results, Kaynia and Kausel [7]. RCDF procedures do not specify steps to follow for considering piles group effects. Thus this consideration was only taken into account in Dyna5 models.

With respect to the piles-soil-box group effect, a simple model proposed by Kobori *et al.* [8] was considered. In a previous work by Taborda [2], it was found that, for the SIS building, this consideration slightly reduced the stiffnesses and was conclude that, at least for this specific case, it is not an influent parameter in the final results. Therefore, stiffnesses values presented here do not include this effect. Anyway, it should be notice that neither RCDF consider this effect nor Dyna5 does it in a clear form.

Then, according with the above assumptions and following the procedures referred, three different models combinations were developed. Model NTC follows the steps presented by RCDF and models D1 and D2 are those prepared with Dyna5 not including and including piles group effect, respectively. It must be remarked that because of the Dyna5 limitations, only piles of circular cross section with a fixed diameter

Table 1. Translation and rocking stiffnesses for NTC model

		JAL Building		SIS Building	
		Static	Dynamic	Static	Dynamic
K_L (N/m x 10^{10})	Piles	0.19 (52 %)	0.19 (52 %)	1.17 (69 %)	1.17 (70 %)
	Box	0.18 (48 %)	0.18 (48 %)	0.51 (31 %)	0.50 (30 %)
	Total	0.37	0.37	1.68	1.67
K_T (N/m x 10^{10})	Piles	0.19 (52 %)	0.19 (52 %)	1.17 (69 %)	1.17 (70 %)
	Box	0.18 (48 %)	0.18 (48 %)	0.51 (31 %)	0.50 (30 %)
	Total	0.37	0.37	1.68	1.67
K_{rT} (N·m/rad x 10^{12})	Piles	1.40 (64 %)	1.59 (69 %)	2.80 (65 %)	2.80 (65 %)
	Box	0.80 (36 %)	0.70 (31 %)	1.48 (35 %)	1.48 (35 %)
	Total	2.20	2.29	4.28	4.28
K_{rL} (N·m/rad x 10^{12})	Piles	0.50 (62 %)	0.56 (67 %)	2.07 (56 %)	2.07 (60 %)
	Box	0.30 (38 %)	0.28 (33 %)	1.65 (44 %)	1.35 (40 %)
	Total	0.80	0.84	3.72	3.42

Table 2. Translation and rocking stiffnesses for D1 model

		JAL Building		SIS Building	
		Static	Dynamic	Static	Dynamic
K_L (N/m x 10^{10})	Piles	0.35 (66 %)	0.35 (66 %)	1.52 (75 %)	1.52 (75 %)
	Box	0.18 (34 %)	0.18 (34 %)	0.52 (25 %)	0.52 (25 %)
	Total	0.53	0.53	2.04	2.04
K_T (N/m x 10^{10})	Piles	0.35 (66 %)	0.35 (66 %)	1.52 (75 %)	1.52 (75 %)
	Box	0.18 (34 %)	0.18 (34 %)	0.52 (25 %)	0.52 (25 %)
	Total	0.53	0.53	2.04	2.04
K_{rT} (N·m/rad x 10^{12})	Piles	3.36 (81 %)	3.36 (83 %)	3.45 (69 %)	3.46 (73 %)
	Box	0.80 (19 %)	0.70 (17 %)	1.55 (31 %)	1.31 (27 %)
	Total	4.16	4.06	5.00	4.77
K_{rL} (N·m/rad x 10^{12})	Piles	1.14 (79 %)	1.14 (80 %)	2.56 (62 %)	2.56 (66 %)
	Box	0.31 (21 %)	0.28 (20 %)	1.58 (38 %)	1.34 (34 %)
	Total	1.45	1.42	4.14	3.90

Table 3. Translation and rocking stiffnesses for D2 model

		JAL Building		SIS Building	
		Static	Dynamic	Static	Dynamic
K_L (N/m x 10^{10})	Piles	0.09 (33 %)	0.09 (33 %)	0.57 (52 %)	0.57 (52 %)
	Box	0.18 (67 %)	0.18 (67 %)	0.52 (48 %)	0.52 (48 %)
	Total	0.27	0.27	1.09	1.09
K_T (N/m x 10^{10})	Piles	0.09 (33 %)	0.09 (33 %)	0.57 (52 %)	0.57 (52 %)
	Box	0.18 (67 %)	0.18 (67 %)	0.52 (48 %)	0.52 (48 %)
	Total	0.27	0.27	1.09	1.09
K_{rT} (N·m/rad x 10^{12})	Piles	0.84 (51 %)	0.76 (52 %)	1.44 (48 %)	1.40 (52 %)
	Box	0.80 (49 %)	0.70 (48 %)	1.55 (52 %)	1.31 (48 %)
	Total	1.64	1.46	2.99	2.71
K_{rL} (N·m/rad x 10^{12})	Piles	0.34 (52 %)	0.32 (53 %)	1.33 (46 %)	1.30 (49 %)
	Box	0.31 (48 %)	0.28 (47 %)	1.58 (54 %)	1.34 (51 %)
	Total	0.65	0.60	2.91	2.63

for all the piles could be considered. Then, for the case of SIS building, in which diameters of piles varies form 1.0 to 1.6 m, a predominant value was selected considering that the majority of the piles have a diameter of 1.2 m. Regard to JAL building, equivalent diameters were used according to the analyzed components of movement.

Results for the three models are shown in tables 1 to 3 for static and dynamic considerations. Stiffnesses values for the piles group and the box are presented separately, and percentages of participation of each of these in the total stiffness is also included aside. Static condition means non-frequency-dependent, and dynamic values are those that belong to estimation according with the identified system frequencies that will be presented in the next section.

Some important aspects from values in tables 1 to 3 stand out. Differences between static and dynamic stiffness are practically negligible. Translation stiffnesses of T and L components calculated with RCDF are the same. In the case of rocking it is seen that for the JAL building values on T component are 60 % less than on L component. In the case of SIS building, this difference is 17 % when considering piles group effect, and 3 % when not. The comparison between models D1 and D2 for the JAL building suggest that piles group effect has more influence in the rocking stiffnesses than in those of translation, with differences with respect to D1 of 60 and 50 %, respectively. While for the SIS building differences are 36 % for rocking and 46 % for translation.

IDENTIFIED FREQUENCIES

Well known methods of spectral analysis and system identification, as those presented by Bendat and Piersol [9] and Beck and Jennings [10], have been used to study the seismic response of the buildings and their SSI characteristics. Several small and moderate size earthquakes have been recorded and analyzed. Results for JAL building during 11 earthquakes between November 1992 and December 1999 can be found in Murià-Vila *et al*. [1]. In the case of SIS building, analysis performed for 8 earthquakes occurred between September 2001 and April 2002 is presented in Taborda [2].

Results from these works show that frequency and damping values of the soil-structure system changes from one earthquake to another. It has been found that dynamic properties of the system are very sensitive to the intensity of the ground motion. JAL building has suffered significant stiffness degradation. Variation of structural parameters has been mainly attributed to different non-linearity sources in the structure. SIS building, which has not suffered any visual damage, also presents low non-linear effects that are believed to be caused for normal accommodation of the non-structural elements and the foundation in new buildings. For this paper, the most intense earthquakes recorded in each one of the buildings have been selected. Their principal characteristics are shown in table 4.

Table 4. Principal characteristics of earthquakes recorded in the buildings

Building	Event	Date	M_W	Ep. Dist. (km)	I_{Arias} (cm/s)	A_{max} Soil (cm/s^2)	A_{max} Base (cm/s^2)	A_{max} Roof (cm/s^2)
JAL	99-3	06/30/1999	7.4	455	20	34	66	304
SIS	01-1	10/08/2001	6.1	44	16	102	58	166

During event 99-3, JAL building showed non-linear response. As a consequence of that it suffered a reduction of 34 % in its frequency with respect to the first event recorded after its second rehabilitation.

This gave rise to resonance problems for T and L modes of vibration, Murià-Vila *et al*. [1]. On the other hand, during event 01-1, SIS building showed a reduction of 10 % in its fundamentals frequencies with respect to the values obtained from an ambient vibration test performed before the instruments were placed.

Fourier spectrums of roof records in both T and L components are shown in figure 3. Maximum spectral amplitudes for the JAL building are concentrated between 0.4 and 1.0 Hz, while in the case of SIS building, significant frequencies are observed up to 5.0 Hz. Figure 3 also includes selected peak amplitudes for identified frequencies values corresponding to the first mode of vibration.

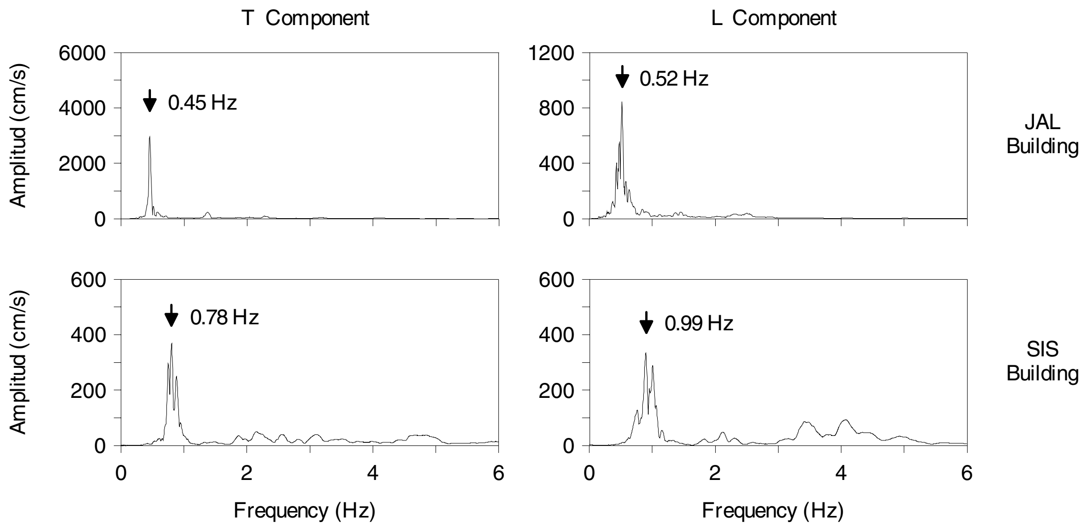

Figure 3. Fourier spectrum of recorded motions at the center of the roof

SSI effects are studied with the simplified method (SIM) proposed by Luco [11] and by using a system identification technique (SID) based on the modal superposition method implemented a computer program developed by Li and Mau [12]. Using both SIM and SID methods, it is assumed that the base is infinitely rigid and that SSI problem could be represented as a sum of different components of deformation contributing to the total response of the system as shown in figure 4.

Simplified Method (SIM)

Let X_T be the total response at the roof of the building, thus it can be written as the sum of the horizontal ground motion (X_G), the relative response at the base (X_0), the response due to rocking of the foundation ($H\phi$) and that one due to the structure deformation itself (X_S), as follows

$$X_T = X_G + X_0 + H\phi + X_S \tag{1}$$

According to this, for the SIM method, the relation of fundamental horizontal vibration frequency of the soil-structure linear system ($\bar{f}_1$) can be written as

$$\frac{1}{\bar{f}_1^{\,2}} = \frac{1}{f_1^2} + \frac{1}{f_R^2} + \frac{1}{f_H^2} \tag{2}$$

where f_1 is the frequency of the fixed-base structure and f_R and f_H are the rocking and horizontal translation frequencies of the rigid structure. Values corresponding to these frequencies can be obtained from the following relations

$$f_R = \bar{f}_1 \left(\gamma_1 \frac{H\phi}{X_T} \right)^{-1/2} \tag{3}$$

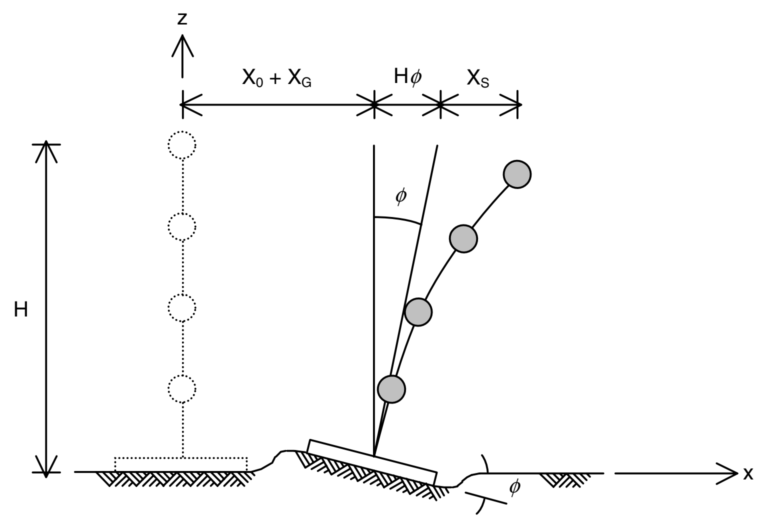

Figure 4. Simplified SSI model

$$f_H = \bar{f}_1 \left(\beta_1 \frac{X_0}{X_T} \right)^{-1/2} \tag{4}$$

Substitution of equations 3 and 4 into 2 leads to

$$f_1 = \bar{f}_1 \left(1 - \gamma_1 \frac{H\phi}{X_T} - \beta_1 \frac{X_0}{X_T} \right)^{1/2} \tag{5}$$

Expressions 3 and 4 can also be related with stiffnesses of translation (K_H) and rocking (K_R) of the base according with the following equations

$$K_H = \beta_1^2 M_1 \left(2\pi f_H \right)^2 \tag{6}$$

$$K_R = \gamma_1^2 M_1 H^2 \left(2\pi f_R \right)^2 \tag{7}$$

where M_1, γ_1 and β_1 are modal parameters associated with the first mode of the fixed-base structure, Luco [11]. Values used for these parameters are presented in table 5.

Following these assumptions, contribution of translation and rocking of the base in the total response can be assessed using the quotients X_0/X_T and $H\phi/X_T$, respectively. Therefore, sum of these two quotients may be interpreted as the total contribution of SSI effects on the translation response at the roof of the building. X_T, X_0 and ϕ quantities were established in terms of the Fourier amplitudes at the identified frequencies. Results for those quotients and the estimated frequencies are presented in table 6. This procedure was also followed for a time moving window analysis and the results will be presented later.

Table 5. Parameters used for SIM method

Parameter	JAL Building		SIS Building	
	T	L	T	L
β_1	1.36	1.43	1.56	1.42
γ_1	0.93	1.01	1.09	0.99
M_1 (kg)	3.89×10^5	3.17×10^5	3.45×10^5	4.17×10^5

Table 6. Identified parameter with SIM method

Building	Comp.	$\bar{f}_1$ (Hz)	f_1 (Hz)	f_R (Hz)	f_H (Hz)	X_0/X_T (%)	$H\phi/X_T$ (%)
JAL	T	0.45	0.51	1.12	2.00	4	17
	L	0.52	0.59	1.23	2.70	3	18
SIS	T	0.78	0.85	2.41	3.97	3	16
	L	0.99	1.17	2.19	3.59	5	30

In addition to the above results, previously decomposing the signal according with the simplified model presented in figure 4, frequencies f_1 were also estimated by selecting the values associated with the maximum ordinate in the spectral ratio RF_S, Meli *et al*. [12].

$$RF_S = \frac{\ddot{X}_T}{\ddot{X}_T - \ddot{X}_S} \tag{8}$$

As a first attempt, frequencies f_R were estimated using the spectral ratios between the vertical records at the edges and the center of the basement. Such quotients presented several ordinates and the most representative were mainly associated with the fundamental frequencies of the soil-structure system. In order to eliminate the presence of the $\bar{f}_1$ frequencies and detect the rocking associated ones it was proposed the ratio RF_R

$$RF_R = \frac{\ddot{X}_T}{\ddot{X}_T - H\ddot{\phi}} \tag{9}$$

Figure 5 shows spectral ratios associated with the fixed-base structure (RF_S) against those of the system ($RF_{Sys} = X_T/X_G$). Also shown in figure 5, indicated by arrows, are the values estimated for f_1 with the SIM method (table 6).

Results for the rocking spectral ratios (RF_R) are shown in figure 6, in which shaded regions indicate frequencies intervals identified as those associated with this component of motion. It is observed that rocking motion is related with multiple frequencies. In the case of the JAL building, amplitudes in the selected range have poor contrast against the rest of the values. This is likely because of the damage suffered by the building during this event. On the other hand, for the SIS building there is a clear contrast within those regions. This procedure is useful to have an idea about the presence and the influence of rocking in the total response.

SID Method

In order to understand the time variation of dynamic parameters of the buildings, data was also analyzed with system identification software with multiple input and multiple output signals, MIMO, Li and Mau [12]. This program uses the modal superposition method proposed by Beck and Jennings [10] for which a structural system, represented as a coupled second order equations system, is transformed into a system of uncoupled equations, each equation having one time-dependent variable. System parameters are determined by using the least squares method. The criterion function is minimized for the time window considered in the analysis for which the system behaviour is assumed to be linear.

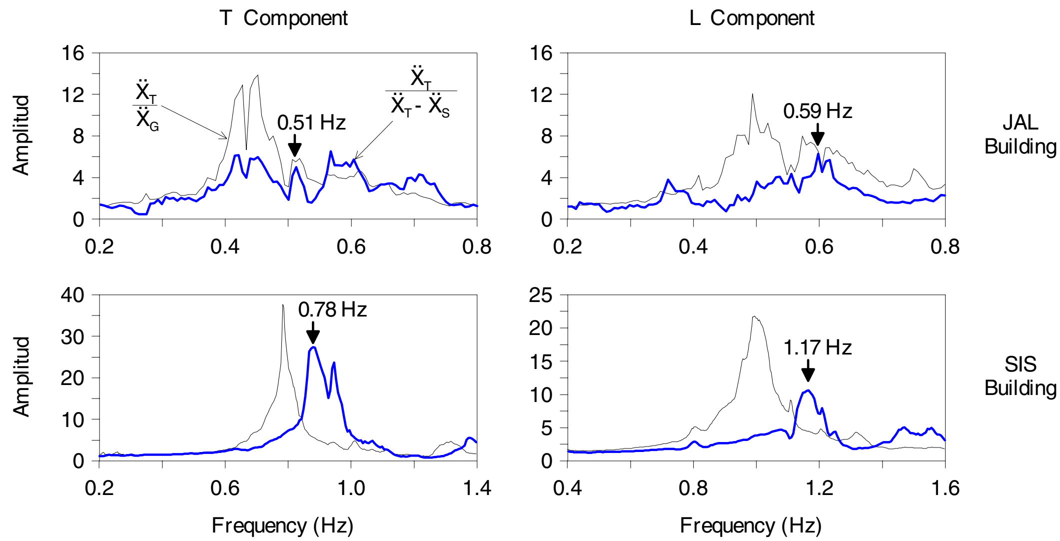

Figure 5. Fixed-base (RF_S) and system (RF_{Sys}) spectral ratios

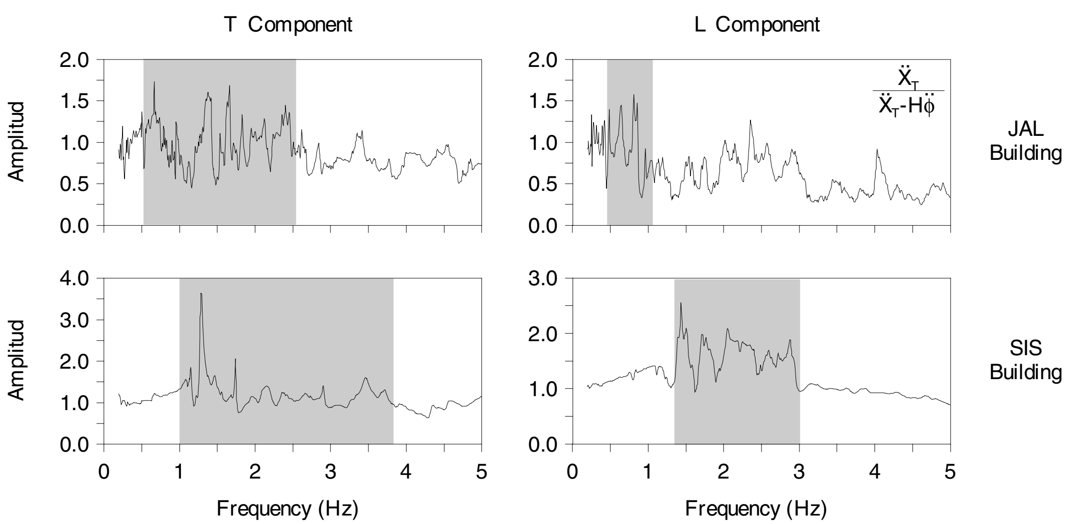

Figure 6. Rocking (RT_R) spectral ratios

Parameters identified in the models considered were the modal frequencies, damping ratios and modal participation factors. Time variation of these parameters under the studied records was assessed by dividing the records in 5 to 10 s windows. Initial values for the first window were set equal to those obtained from the spectral analysis, while for the following windows estimations those from the previous ones were used.

For the case of the soil-structure system, parameters above mentioned were identified by a simple model which output signals were relative acceleration responses in both components of translation as well as torsional acceleration at the roof of the buildings. Input signals were those from records at the free-field stations. Accuracy of such a model has been sufficiently studied and it is known that this simple model leads to excellent results compared with more detailed considerations, Zapata-Escobar *et al*. [14].

Results for the system frequency using the described model for the analyzed events are shown in figures 8 and 9 for the JAL and the SIS building, respectively (empty circles). It can be seen from these figures how sensitive the frequency is to the intensity of input motion.

For the fixed-base structure and rocking frequencies two models were used with the MIMO program (figure 7). No model was developed to identify the frequencies of the relative translation of the base because of its poor contribution to the total response of the system. For the fixed-base structure model, the input motions are the records at the basement plus the correspondent contribution of rocking (E_T and E_L) and the output motions are the relative responses at the roof (R_T, R_L and R_R). Results are shown in figures 8 and 9 (empty circles).

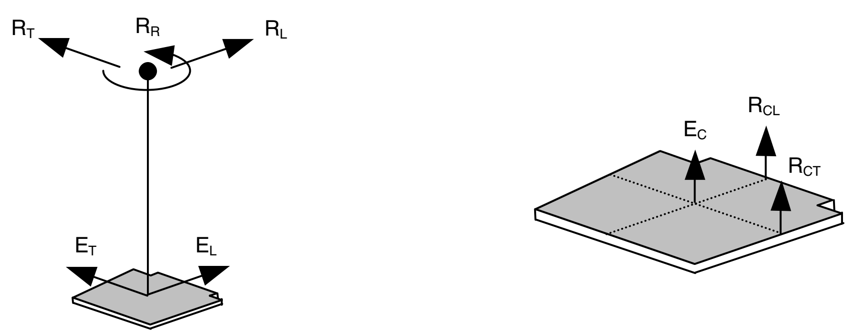

Figure 7. Fixed-base structure (left) and base rocking (right) models for SID method

Regard to the model used for estimating the rocking frequencies in the L and T components, the input motion (E_C) was the acceleration at the center of the basement and the outputs (R_{CL} and R_{CT}) were those from the edges in each one of the components (figure 7). Signals were filtered in order to avoid the influence of the fundamental frequencies and to be able of identifying the rocking frequencies.

COMPARISONS

Frequencies

Figures 8 and 9 show accelerograms recorded at the roof of the buildings in each component. In the second pair of graphics, frequencies of the system obtained with the SID method (empty circle) are plotted against the identified value in the system spectral ratio, RF_{Sys} (continues line). Third pair of graphics show fixed-base structure frequencies estimated with SIM method applied in a moving window analysis (solid circles), SID method (empty circles) and RF_S spectral ratio (continues line). Last pair of graphics show identified frequencies associated with the rocking motion of the base. Solid circles belong to the values founded with the SIM method, while empty circles are those from application of SID method. For the latter, size of the circles are associated with the participation factor of the identified frequencies in the filtered rocking response. Shaded regions are the same that were identified in the spectral ratio, RF_R, and presented before in figure 6. Arrows at the sides belong to frequency values reach from the stiffnesses assessed with RCDF (thin) and Dyna5 models D1 (thick simple head) and D2 (thick triangle head) using the relation defined by equations 6 and 7. Those arrows at the left side of each frame were calculated from the sum of both piles and box stiffnesses. While those at the right side were calculated just using the piles stiffnesses.

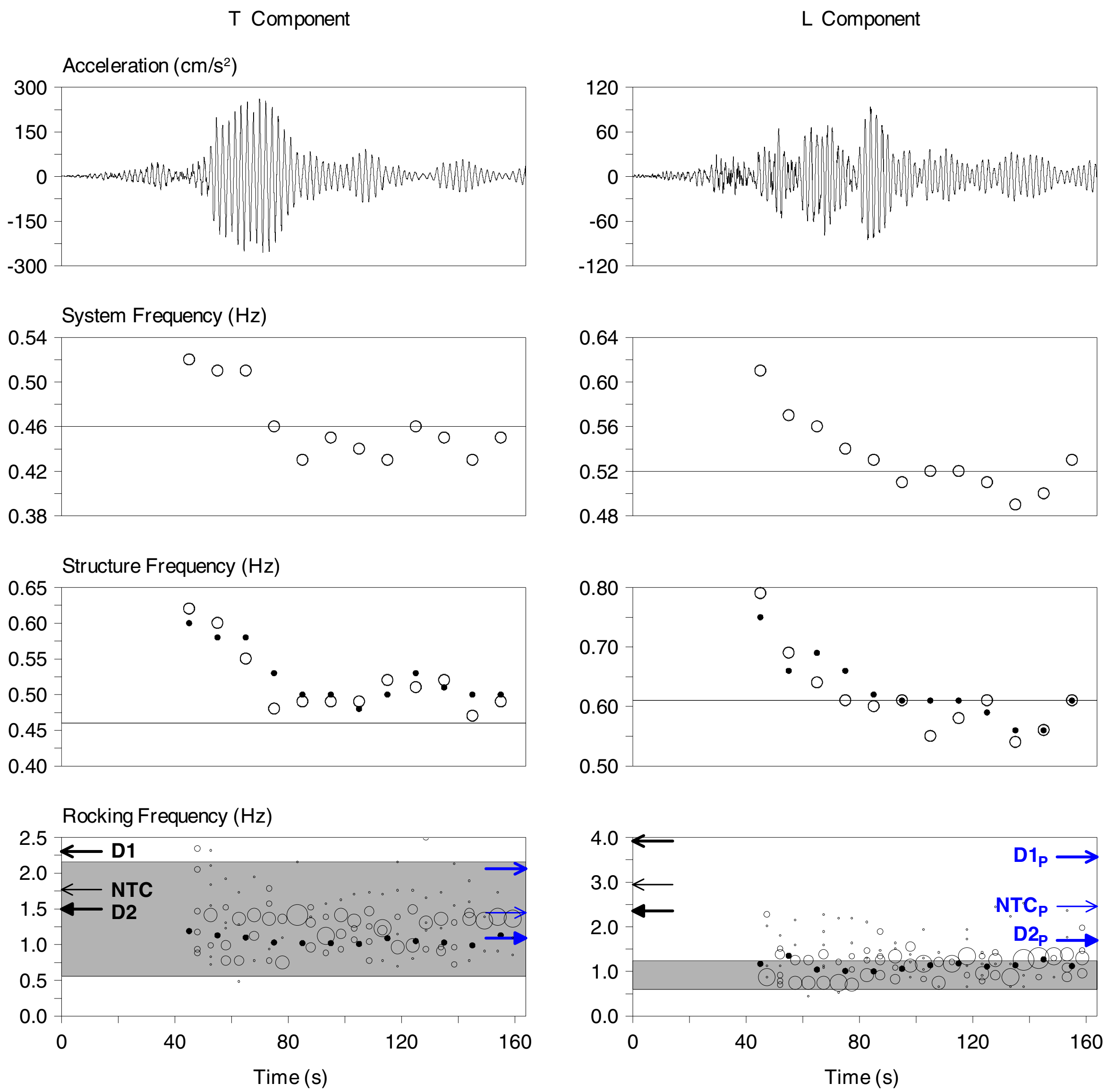

Figure 8. Identified and estimated frequencies for the JAL building

From these figures it can be seen that fixed-base and soil-structure system frequencies have similar amplitude-dependence on the input motion. In the case of the fixed-base structure, both SIM and SID methods leads to very similar results. It must be also noticed that the major reductions on these frequencies occurred during the intense phase of the events.

On the other hand, values of the rocking frequency do not show a clear tendency, neither from the SIM nor from the SID method. This indicates that the variations of the system frequency can not be clearly related with the variations of the rocking frequencies, suggesting that sources of non-linearities detected in the systems are mainly due to the structure. Nevertheless, this can not be interpreted as an underestimation of the influence of the rocking motion in the total response of the buildings or the influence of the SSI effects themselves.

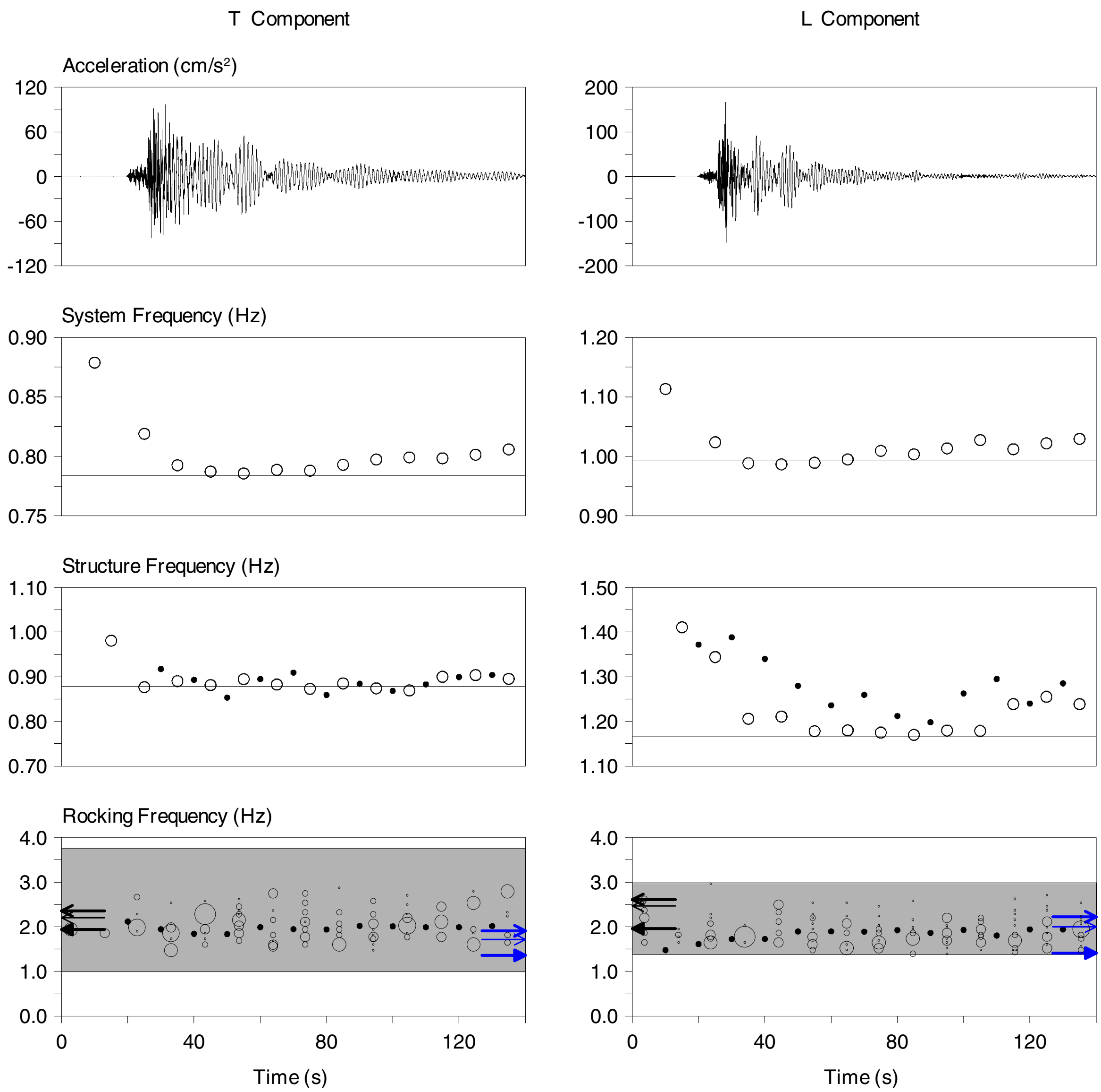

Figure 9. Identified and estimated frequencies for the SIS building

Results from models of the SID method show several participating frequencies and varies from one component to another, although at the same time they reveal that T and L components are coupled. It should be noticed that those frequencies with the major participation factors (i.e. greatest circles) do not match well with the values estimated with the SIM method, neither they are consistent with some of the different analytical models values represented by the arrows.

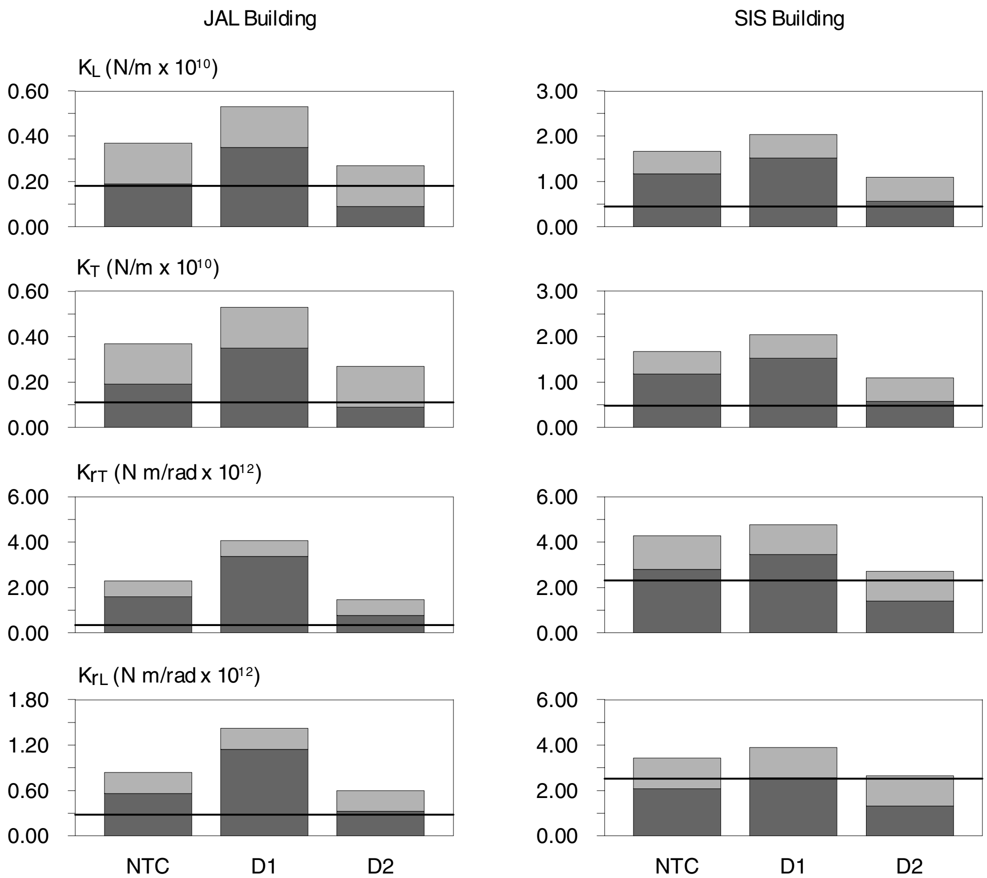

Figure 10. Estimated stiffnesses from analytical models and SIM method

Stiffnesses

Although it has been seen in the previous section that it is not possible to define a unique value for the frequency of the rocking component of movement, let us assume that those values obtained from the SIM method are representative enough to go further in comparing the stiffnesses assessed from the estimated frequencies and the relations established in equations 6 and 7, and compare the results from them with the stiffnesses obtained with the different analytical models. Figure 10 shows with bars the values of NTC, D1 and D2 models against the correspondent value obtained with the SIM method (horizontal line). Contribution of the piles is in dark gray and contribution of the box is in light gray.

Comparison of these stiffnesses in figure 10, leads to the following remarks:

- Stiffnesses obtained with the Dyna5 model that does not consider piles group effect (D1) as well as those from the RCDF procedures (NTC model) are much higher than the corresponding values of the SIM method, while the values from the model that does consider such effects (D2) are closer.

- Except for the rocking components in the SIS building and the horizontal translation on L in the JAL building, it seems that the most appropriate representation should be taking only the contribution of the piles considering the piles group effect (i.e. dark gray part in model D2). On the other hand, the mentioned exceptions are closer to the values that also consider the contribution of the box, in model D2.

FINAL COMMENTS

Results of a simplified model (SIM) and analysis from different spectral ratios are compared with a system identification method (SID) to estimate the frequencies of two instrumented buildings and their components of movement. It was found that SID method is useful when estimating the system, fixed-base structure and base rocking frequencies. It was no possible to identify the base translation frequency because of its low contribution to the total response of the systems studied.

From both the system and the fixed-base structure models, it was found that the dynamic responses are very sensitive to the amplitude of the imposed ground motion, even for small levels of excitation. The main factor affecting the vibration frequencies was found in the non-linear behavior of the superstructures, suggesting that these non-linearities are associated with structural and non-structural elements.

The study revealed that the rocking movement is associated to several frequencies. Difficulties in identifying this movement may be possibly related with contact pressures at the soil-foundation interface due to the averaging effect of the incident waves and the structural forces and moments which incorporate new sources of vibration. Progress on the study of the SSI effects may be enhanced if base instrumentation of the buildings were improved, mainly to have data available about contact pressures and rotational movements. This will let us go forward in understanding the effects of varying contact pressures at the soil-foundation interface and their implications on the structural response during successive seismic events.

Regarding the associated values of the foundation stiffnesses, results suggest that in almost all the components of movement, the contribution of the box could be ignored. Although this may be expected for the JAL building because of the loss of contact at the basement-side-walls, it does not seem so clear for the SIS building in which this contact loss should not be expected, especially in relation with the horizontal translation of the base, since it is a recent structure. It is also clear that piles group effects must be considered.

Finally, as pointed out before by different authors, the consideration of both piles group effects and loss of base contact as well as the frequency amplitude-dependency, constitute two factors that ought to be incorporated into future building codes. Practice engineers must be encouraged to think on the most adverse condition when taking into account SSI effects. This also highlights the importance of performing full-scale tests in order to verify real practice applications.

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REFERENCES

1. Murià-Vila D, Rodríguez G, Zapata A, Toro A M. "Seismic response of a twice-retrofitted building." ISET Journal of Earthquake Technology 2001; 38 (2-4): 67-92.
2. Taborda R. "Respuesta dinámica y efectos de interacción suelo-estructura de un edificio instrumentado en Acapulco." M.Eng. Thesis, División de Estudios de Posgrado, Facultad de Ingeniería, UNAM, Mexico, 2003.
3. Alcántara L, Murià-Vila D, Almora D, Velasco J M, Torres M, Vázquez R, Vázquez E, Macías M. "Sistema de monitoreo remoto en un edificio localizado en una ciudad expuesta a un peligro sísmico mayor." Octavas Jornadas Chilenas de Sismología e Ingeniería Antisísmica, Valparaíso, Chile, 2002.
4. NTCDS-RCDF. "Normas Técnicas Complementarias para Diseño por Sismo del Reglamento de Construcciones para el Distrito Federal. Versión Preliminar." VI Simposio Nacional de Ingeniería Sísmica, Sociedad Mexicana de Ingeniería Sísmica A.C., Mexico, 2000.
5. Novak M, Sheta M, El-Hifnawi L, El Marsafawi H, El Naggar H, Ramadan O, El-Sawy K. Dyna5® for Windows 95®, Geotechnical Research Centre, University of Western Ontario, 1995.
6. Novak M. "Piles under dynamic loads." Proceedings of 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Luis, Missouri, 1991: 2433-2455.
7. Kaynia A M, Kausel E. "Dynamic behavior of piles groups." Proceedings of 2nd International Conference on Numeric Methods Offshore Piling, Austin, Texas, 1982: 509-532.
8. Kobori T, Nakazawa M, Hijikata K, Kobayashi Y, Miura K, Miyamoto Y, Moroi T. "Study on dynamic characteristics of a pile group foundation." Proceedings of 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Luis, Missouri, 1991: 853-860.
9. Bendat J S, Piersol A G. "Random data. Analysis and measurement procedure." Wiley Interscience, New York, 1989.
10. Beck J L, Jennings P C. "Structural identification using lineal models and earthquake records." Earthquake Engineering and Structural Dynamics, 1980; 8: 145-160.
11. Luco J E. "Soil-structure interaction and identification of structural models." Proceedings of 2nd ASCE Conference on Civil Engineering and Nuclear Power, Knoxville, Tennessee, 1980; 3(10): 10.1-10.30.
12. Li Y, Mau S T. "A computer program for multiple input - multiple output system identification using building seismic records." Research Report UHCEE 90-07, Department of Civil and Environmental Engineering, University of Huston, 1990.
13. Meli R, Faccioli E, Murià-Vila D, Quaas R, Paolucci R. "Study of site effects and seismic response of an instrumented building in Mexico City." Journal of Earthquake Engineering 1998; 2(1): 89-111.
14. Zapata-Escobar A, Murià-Vila D, Rodríguez G. "Efectos de interacción suelo-estructura." Instituto de Ingeniería, UNAM, GDF, Mexico, 2002: Proj. 1542.