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INFLUENCE OF SOIL-STRUCTURE INTERACTION AND SUBSOIL CONSOLIDATION IN THE SEISMIC RESPONSE OF A BUILDING

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Abstract

Nowadays, there are a few dozen of seismically-instrumented buildings in Mexico, from which one of the best instrumented was selected for this paper (PC building). The building is a 17-storey reinforced concrete structure located in Mexico City. It is founded on soft soil through an embedded box supported on friction piles. The building is one of the several structures that were damaged during the Michoacán earthquake (September 19th of 1985, Mw =8.1) and it was later retrofitted.

Since 1990 an accelerometer network is operating in the building. Twenty-five seismic events have been recorded and analyzed through these 26 years of continuous monitoring. The maximum responses recorded in the building until 2015 in terms of maximum acceleration and displacement have been 0.22 g and 24 cm respectively. The maximum drift, calculated by dividing the relative displacements by the vertical distance between instrumented stories, has been 0.55%.

The purpose of this paper is to present the variations of the vibration frequencies of the soil-structure system and the vibration frequencies of the structure excluding the effects of soil-structure interaction (SSI). In addition, the influence of the building damage and of the increase of the site dominant frequency in defining the vibration frequency of the whole soil-structure system is discussed.

The analyses of the aforementioned records are studied with a simplified model and by using a system identification technique based on the Modal Minimization Method (MM model). Both models are used to identify the vibration frequencies of fixed-base buildings and to evaluate if the frequency variations of the systems correlate with SSI effects. It was found that the MM model is a useful tool for identifying the frequencies of the fixed base building, the movement of the base, and of the whole system.

Keywords: structural monitoring, earthquake records, soil-structure interaction, subsoil consolidation, structural damage

1. Introduction

Currently, there are a few dozens of seismically-instrumented buildings in Mexico City, but only few of them have enough instruments that may help visualize a global response of the building during an earthquake. One of these buildings, known as PC building (Fig. 1) is the subject of this paper.

The PC building is a 17-storey reinforced concrete structure located in Mexico City and founded on soft soil. It was erected in the eighties and finished before the great earthquake of September 1985 [1]. The base floor has 38 m in the transversal direction (T) and 54 m in the longitudinal direction (L). From bottom to top, the building consists of a mezzanine, five levels for parking, and 12 office stories with a typical floor of 32 by 40 m in the T and L directions respectively. The foundation consists of a reinforced concrete box buried at 3.3 m and supported by 266 friction piles (Fig. 1).

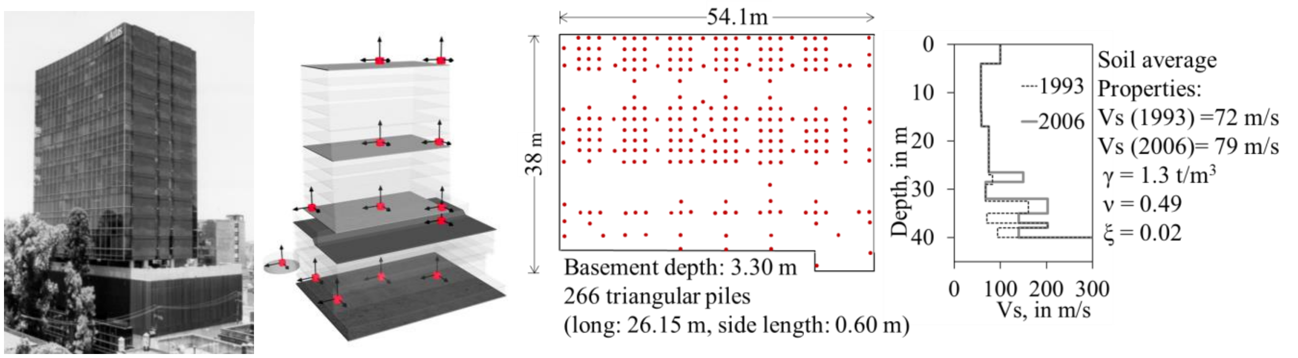

Fig. 1 – The PC building, its instrumentation, foundation plans and relevant soil properties

On 1985 earthquakes the structure sustained moderate damage, which mainly occurred in the transition between the parking levels and the tower. These damages were repaired and additionally the structure was strengthened by replacing the masonry walls along its height for reinforced concrete ones [1, 2]. On April 25, 1989 an earthquake which on-site effects were of moderate intensity, caused slight damage to the building, thus producing a decrease in the frequencies of vibration of the building as reported by Rodríguez and Quaas [2]. However the type of damage and the decrease of the vibration frequencies were not detailed.

The main purpose of this work is to present the variations of the vibration frequencies of the whole soil-structure system and of the structure itself excluding the effects of soil-structure interaction (SSI). Twenty-five seismic events have been recorded and analyzed through these 26 years of continuous monitoring. In addition, the influence of the building damage and of the increase of the site dominant frequency in defining the vibration frequency of the whole soil-structure system is discussed.

The analyses of the aforementioned records are studied with a simplified model and by using a system identification technique based on the Modal Minimization Method (MM model). Both models are used to identify the vibration frequencies of fixed-base buildings and to evaluate if the frequency variations of the systems correlate with SSI effects. It was found that the MM model is a useful tool for identifying the frequencies of the fixed base building, of the base rocking, and of the whole system.

2. Structural Monitoring

2.1 Seismic records

In 1990, an array of 11 tri-axial accelerometers was installed in the building [1, 2]. Afterwards, in 1999, two accelerometers were added to study the effects of soil-structure interaction (SSI). One was installed in the ground and another one in the south corner of the building's base. The array of the 13 sensors installed in the structure is shown in Fig. 1. With this instrumentation several seismic events have been recorded, in this work twenty-five of the most representative are presented [3]. The maximum responses recorded in the building until 2015 in terms of maximum acceleration and displacement have been 0.22 g (220 cm/s^2) and 24 cm respectively.

The maximum drift, calculated by dividing the relative displacements by the vertical distance between instrumented stories, has been 0.55%.

The seismic events are analyzed with a structural health monitoring system "AlertaE" to estimate the possible global damage of the building [4]. The system is based on five indicators. The first two are ground motion parameters: peak ground acceleration (PGA) and Arias Intensity (I_{Arias} [5]). The other three are structural demand parameters: seismic coefficient (Cs), interstory drift (SD) and variation of fundamental horizontal translation frequencies (VF) (Table 1).

Table 1 – Thresholds of the indicators for RC buildings of medium height on Mexico City soft soil

Level	PGA in cm/s^2	I_{Arias} in cm/s	Seismic coefficient (Cs)	Interstory drift (SD) in %	Variation of frequency (VF) in %
1	< 15	< 5	< 0.03	< 0.12	< 7
2	15 - 130	5 - 140	0.03 - 0.16	0.12 - 0.60	7 - 25
3	> 130	> 140	> 0.16	> 0.60	>25

Table 2 – Characteristics of seismic events and estimated structural condition of the building

Event	Date	Mw	Ep. Dist. in km	PGA in cm/s^2	I_{Arias} in cm/s	Cs	SD in % L	SD in % T	VF in % L	VF in % T	Damage level from event 90-1	Damage level from event 1989
90-1	31/05/1990	5.3	316	7	0.8	0.01	0.08	0.15	0.0	0.0	Light	Intermediate
91-1	01/04/1991	5.4	384	3	0.2	<0.01	0.04	0.03	-0.9	0.9	Light	Intermediate
93-4	15/05/1993	6.1	334	10	1.5	<0.01	0.05	0.04	-0.6	-0.6	Light	Intermediate
93-11	24/10/1993	6.7	319	13	2.9	0.02	0.16	0.17	2.0	1.1	Light	Intermediate
94-1	23/05/1994	6.3	215	6	0.5	<0.01	0.03	0.02	-0.8	-0.8	Light	Intermediate
94-3	10/12/1994	6.5	298	17	6.9	0.03	0.20	0.34	6.3	6.6	Intermediate	Intermediate
95-1	14/09/1995	7.5	345	30	21.4	0.04	0.36	0.55	10.9	10.0	Intermediate	Intermediate
95-2	09/10/1995	7.9	586	17	9.8	0.04	0.19	0.27	8.4	5.6	Intermediate	Intermediate
97-1	11/01/1997	7.1	443	18	8.2	0.05	0.39	0.29	12.7	11.5	Intermediate	Intermediate
97-2	22/05/1997	6.5	302	5	0.4	<0.01	0.07	0.07	4.6	3.6	Light	Intermediate
99-1	15/06/1999	6.7	223	28	17.6	0.03	0.20	0.42	7.3	5.9	Intermediate	Intermediate
99-2	21/06/1999	5.8	311	6	0.7	0.01	0.05	0.06	4.8	6.1	Light	Intermediate
99-3	30/09/1999	7.4	437	27	20.9	0.03	0.26	0.47	9.4	8.2	Intermediate	Intermediate
99-4	29/12/1999	5.9	304	6	0.7	<0.01	0.08	0.07	3.3	3.6	Light	Intermediate
07-1	13/04/2007	6.3	292	14	2.4	0.01	0.07	0.08	1.1	3.3	Light	Intermediate
11-3	10/12/2011	6.5	196	21	4.6	0.03	0.08	0.12	1.9	0.9	Light	Intermediate
12-1	20/03/2012	7.4	359	43	29.0	0.05	0.30	0.30	7.4	5.7	Intermediate	Intermediate
13-2	16/06/2013	5.8	154	25	6.4	0.03	0.11	0.12	2.2	3.6	Intermediate	Intermediate
13-3	21/08/2013	6	296	10	1.5	0.01	0.06	0.07	2.4	5.0	Light	Intermediate
14-1	18/04/2014	7.2	329	47	30.9	0.05	0.23	0.38	7.0	11.6	Intermediate	Intermediate
14-2	08/05/2014	6.4	315	37	14.5	0.05	0.20	0.39	6.6	6.8	Intermediate	Intermediate
14-3	10/05/2014	6.1	324	10	1.6	0.02	0.07	0.11	9.6	13.3	Light	Intermediate
14-4	07/07/2014	6.9	868	6	0.8	<0.01	0.06	0.05	7.3	5.1	Light	Intermediate
14-5	29/07/2014	6.4	417	5	0.2	<0.01	0.03	0.04	7.3	0.0	Light	Intermediate
15-1	20/03/2015	5.4	173	5	0.3	<0.01	0.01	0.02	7.3	6.2	Light	Intermediate

For each indicator a scale of three levels of possible damage is proposed: possible light damage (Level 1), possible intermediate damage (Level 2) and possible severe damage (Level 3). The three levels of damage are defined for each indicator by setting thresholds, which are a function of the building characteristics (structure and non-structural elements), site location characteristics, and the structural condition when monitoring begins.

The description of light, intermediate and severe damage is presented in Murià-Vila *et al.* [4]. The threshold values used for the PC building are shown in Table 1.

The structural condition of the building is established by weighting the five indicators, based on four colors: Green, when VF, SD, PGA, I_{Arias} and Cs belong to level 1. Yellow, when VF or SD, or two of the remaining intensity indicators match level 2. Orange (building inspection) may be determined when VF or SD is level 3 and at least one indicator PGA, I_{Arias} or Cs is level 2, or VF is level 2 and one of the other indicators is level 3. Orange state, indicates an urgent need to inspect the building to exclude a red-state case. Red, is established when the inspection suggests evacuating the building.

If the event 90-1 is considered as initial state, ten of the set seismic records events reached the yellow level (Table 2). The ground motion indicators (PGA and I_{Arias}) were at maximum at the events 12-1 and 14-1, and the greatest values in the history of the building, followed by the event 95-1. As for the variation of frequencies, in the L component the indicator was level 2 in four events and in the T component in the events 95 - 1 and 99-3. When applying this system alerts, it is determined that events 94-3, 95-1, 99-1, 99-3, 12-1, 13-2, 14-1 y 14-2 reach the Yellow state. Subsequent events of lower intensity show that the VF indicator partially recovers its initial value, thus corresponding to a Green state damage with respect to the event 90-1.

2.2 Observed damages

The interstory drifts (SD) analyses show that none of the values exceed the limits permitted by the building codes of Mexico City. Major drifts on the T component were found during events 95-1 and 99-3 with 0.55 and 0.47 % values respectively. Major drifts on the L component were found on 95-1 and 97-1 events, reaching 0.36 and 0.39 % values respectively. Structural inspections after Yellow-state indicators previous to 2012 were catalogued as light damage take into account the define damage level [4]. Authors had the opportunity to carry out inspections since 2000. Inspections after the most intense events recorded, 12-1 and 14-1 (Yellow state) revealed damage of non-structural facades, partition walls and finishing, and also the reopening of cracks found in original structural elements, but not reaching 1 mm in width. Furthermore similar size cracks were also found on the walls built to retrofit the structure. Therefore, the level of damage should be considerate as intermediate.

Likewise, the building shows evidence of uniform relative emersion of tens of centimeters with respect to the street-level, indicating that the piles are supported by a hard stratum. In front of this fact, information was requested to the owner of the building. Topographical data (from September 1986 – December 2014), a building inspection and a geotechnical study (both carried out in 2006) were provided the owner. Topographical data showed that total emersion from 1986 to 2014 is 882 mm without tilting problems. During the first four years, the emersion annual rate was very slow (from 2 to 10 mm), gradually increasing since event 90-1. From 1993 until today, the average emersion annual rate has been stabilized around 34 mm, denoting that piles tip condition could changed from floating to end bearing during the early 90’s.

2.3 Variation of the frequencies

The vibration frequencies are obtained by applying a spectral analysis [6] to the seismic and ambient vibration records. Because of space limitations, this paper will only address the horizontal translation frequencies considered in the structural warning. In the spectral analysis, it is found that the frequency ranges of maximum amplitudes corresponding to the fundamental modes of L and T components are overlapping, due to the non-linearity of the building’s dynamic response and the interaction between these modes.

The dominant frequency of the site between 1990 and 2015 varied from 0.40 to 0.51 Hz, defining an annual variation rate of 0.0037 Hz. This is mainly caused by the great exploitation of the underground aquifers in Mexico City, originating soil consolidation, and the modification of the static and dynamic subsoil properties [7]. Therefore, the variation of the system frequencies are attributed to different non-linearity sources and the decrease of the soil dominant period. The increase of system fundamental frequencies observed during the first four years of seismic response monitoring of the building (Table 2, events 91-1, 93-4, 94-1) was due to the effects of soil consolidation and the gradual process of piles contact with the hard stratum.

In order to study the time variation of the dynamic parameters of the building, data from the most significant seismic events (90-1, 95-1, 99-1, 99-3, 12-1 and 14-1) was also analyzed through a parametric methodology based on the minimization of the differences between the measured acceleration signals and the ones calculated with a simplified modal superposition model [8]. This methodology was improved and adapted into a semiautomatic procedure for the analysis of seismic records in instrumented buildings [9] validated and compared with other common system identification methods using analytical models and records from instrumented buildings. Time variation of the frequencies was assessed by dividing the records in time windows of 5 to 10 s.

The system frequencies were identified by a model which output signals were the relative acceleration responses in both components of translation, as well as torsional acceleration at the roof of the building. Input signals were those from records at the field station. The identified frequencies of the system using the described model for the analysed events are shown in Fig. 2 (solid circles) with the values estimated from the system spectral ratio, RF_{System} (shaded region). It can be seen from this figure how sensitive the frequency is to the intensity of input motion. Table 3 summarizes the fluctuation of the frequencies values corresponding to the initial and final low intensity phases and the high intensity phase of motion for the selected events.

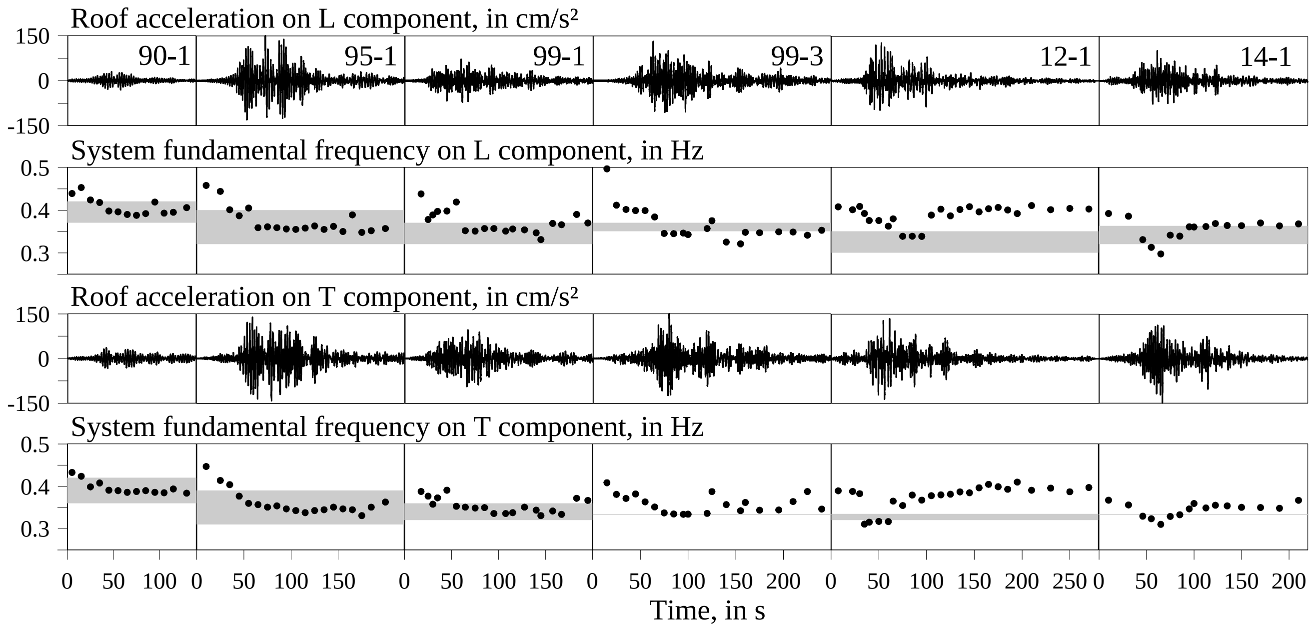

Fig. 2 – Estimated frequencies in L and T components of the building

Table 3 – Summary of variation frequencies of the system from the most significant seismic records

Event	Component L			Component T		
	f_i	f_s	f_f	f_i	f_s	f_f
90-1	0.446	0.388	0.401	0.429	0.384	0.388
95-1	0.451	0.348	0.355	0.431	0.331	0.357
99-1	0.408	0.331	0.390	0.383	0.331	0.372
99-3	0.412	0.321	0.350	0.395	0.334	0.352
12-1	0.404	0.339	0.403	0.389	0.311	0.394
14-1	0.386	0.298	0.370	0.356	0.310	0.350

f_i - frequency of initial phase, f_s - frequency of intense phase, f_f - frequency of final phase (in Hz)

After the events of 1995, the final segment of L and T components present a frequency drop about 11.6%. In the low intense event of 1997 (97-1, Table 2) the building partially recover the frequencies values. Nevertheless, when moderate intense events occurred during 1999, 2012 and 2014, frequency reduction were registered again, 12.6% in 1999 and 9.7% in 2014. The drop in frequency values for moderate intensity events with respect to 90-1 event, in spite to consolidation of soil, suggests that the main damage occurred in 1995. The values from subsequence events of low intensity recorded between the moderate events showed similar reductions, and a partially recover of values is observed after the events of 1995. It has been observed that the restoration of the internal finishing affected by an event produce a partially recover of the response frequency.

Regarding the ambient vibration records, the frequencies from measurements after rehabilitation works for the building in January 1989 [2] are available. In addition, frequencies from two tests conducted before the events 99-3 in 1999 (VA2) and 07-1 in 2006 (VA3) were considered. In Table 4 the frequencies obtained from ambient vibration test and the variation of frequencies VA2 and VA3 relative to VA1 (1989) are presented. Frequency decreases are similar, despite event 99-3 presented a lower intensity than April 25, 1989 earthquake, suggesting that the structure was damaged prior to its instrumentation in 1989, being the most intense event occurred after rehabilitation [3]. This means that after the earthquake in April 25, 1989 the level of damage in the building is intermediate, according to the classification of the structural health monitoring system "AlertaE" [4].

Table 4 – Ambient vibration frequencies and differences respect to test VA1

Test	Date	Frequencies, in Hz		Variation, in %	
		L	T	L	T
VA1	15/01/1989	0.56	0.56	0.0	0.0
VA2	25/06/1999	0.49	0.44	-12.5	-21.4
VA3	04/04/2006	0.475	0.44	-15.2	-21.4

3. Soil-structure interaction (SSI) effects

A simplified model (SIM) proposed by Luco [10] was used to estimate the contribution of the soil-structure system (SSI) effects on the response of the building and to identify the fixed-base frequencies. Furthermore, this model was use to explore if the variation of system frequencies (presented in the previous section) correlated with SSI effects. In addition to the SIM method, these effects were also studied using a system identification technique based on the modal minimization method (MM) implemented in a computer program [9], the same used in the identification of the system frequencies in time windows.

3.1 SIM method

According to the Luco method, the total response at the roof of the building X_T can be written as follows

$$X_T = X_B + H\phi + X_s \tag{1}$$

where X_B is the response due to the translation of the base, $H\phi$ is the response due to rocking of the foundation and X_S is due to the structure deformation itself. X_B is the sum of the horizontal ground motion (X_G) and the relative response at the base of the building (X_o), H is the total height of the structure and ϕ is the base rocking.

The fundamental horizontal vibration frequency of the soil-structure 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, f_H and f_R are the horizontal translation and rocking frequencies of the rigid structure. The values of these frequencies can be obtained from

$$f_H = \bar{f}_1 \left(\beta_1 \frac{X_B}{X_T} \right)^{-1/2} \tag{3}$$

$$f_R = \bar{f}_1 \left(\gamma_1 \frac{H\phi}{X_T} \right)^{-1/2} \tag{4}$$

where β_1 and γ_1 are modal parameters of the first mode of the fixed-base structure. Substitution from Eqs (3) and (4) into Eq (2) leads to

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

By means of these equations and the fundamental frequencies of the system $\bar{f}_1$ obtained in the previous section, the SSI effects in T and L directions can be analysed. The total contribution of SSI effects on the translation response at the roof of the building can be assessed with the sum of the quotients X_B/X_T and $H\phi/X_T$. X_T, X_B and ϕ quantities were established in terms of the Fourier amplitudes at the identified frequencies. To calculate f_H and f_R the adopted values for β_1 and γ_1 are presented in Table 5. $\bar{f}_1$ is estimated for each event with the whole record, then it can differ of value in Table 2 because those were estimated with the final phases of the record. Results for those quotients, frequencies ratios $f_1/\bar{f}_1$ and estimated frequencies for several of the recorded events are presented in Table 6.

Table 5 – Parameters used for SIM method

Parameter	L	T
β_1	1.54	1.62
γ_1	1.09	1.17

The contribution of the translation and rocking of the base in the total translation response at the roof of the building in T and L directions is different. In L component the translation effect is overriding, and in T component the rocking effect is more dominant. The relationship between the frequencies of the structure and those obtained for the system $f_1/\bar{f}_1$ is another indicator of the SSI effects. These values ranging between 1.06 and 1.14. The SSI effects were more meaningful in the response of the building in T component.

Table 6 – Identified parameter with SIM method

Event	L Component							T Component						
	$\bar{f}_1$ (Hz)	f_1 (Hz)	f_H (Hz)	f_R (Hz)	$\frac{f_1}{\bar{f}_1}$	$\frac{X_B}{X_T}$ (%)	$\frac{H\phi}{X_T}$ (%)	$\bar{f}_1$ (Hz)	f_1 (Hz)	f_H (Hz)	f_R (Hz)	$\frac{f_1}{\bar{f}_1}$	$\frac{X_B}{X_T}$ (%)	$\frac{H\phi}{X_T}$ (%)
99-1	0.351	0.382	0.941	2.709	1.09	9	2	0.327	--	0.954	--	--	7	--
99-2	0.366	0.388	1.202	3.074	1.06	6	1	0.354	0.403	1.096	1.005	1.14	6	11
99-3	0.363	0.386	1.216	2.324	1.06	6	2	0.333	0.375	1.023	1.023	1.13	7	9
99-4	0.366	0.388	1.229	2.619	1.06	6	2	0.354	0.395	1.081	1.191	1.11	7	8
07-1	0.375	0.405	1.093	2.448	1.08	8	2	0.360	0.397	1.260	1.162	1.10	5	8
11-3	0.375	0.404	1.087	2.859	1.08	8	2	0.357	0.408	1.115	0.987	1.14	6	11
12-1	0.336	0.365	0.913	2.415	1.09	9	2	0.323	0.363	0.974	1.048	1.12	7	8
14-1	0.333*	0.365	0.944	1.562	1.10	8	4	0.333*	0.369	1.061	1.121	1.11	6	8
14-2	0.336	0.366	0.956	1.778	1.09	8	3	0.323	0.357	1.050	1.104	1.10	6	7
14-3	0.342	0.367	1.030	2.241	1.07	7	2	0.330	0.368	1.020	1.082	1.12	6	8

*Estimated with AC/SC spectral ratio

Additionally to the above results and according with the simplified model, frequencies f_1 were also estimated by selecting the values associated with the maximum ordinate in the spectral ratio RF_S [11] defined as

$$RF_S = \frac{X_T}{X_T - X_S} \tag{6}$$

Similarly, to estimate the frequencies f_H and f_R, the following spectral ratios are proposed

$$RF_R = \frac{X_T}{X_T - H\phi} \tag{7}$$

$$RF_B = \frac{X_T}{X_T - X_B} \tag{8}$$

Fig. 3 shows spectral ratios associated with the fixed-base structure (RF_S) against those of the system ($RF_{System} = X_T/X_G$). The values estimated for f_1 with the SIM method are also indicated with arrows (Table 6).

Results from translation base spectral ratio (RF_B) and rocking spectral ratios (RF_R) are shown in Figs. 4 and 5, in which shaded regions indicate frequencies intervals identified as those associated with this component of motion. It is observed that translation base and rocking motion are related with several frequencies. This procedure is useful to have an idea about the presence and the influence of translation and rocking base motion in the total response. RF_R results present a poor contrast against the rest of the values, thus complicating the identification of a clear frequency band of influence. For $RF_{B,}$ results present a better definition, thus being possible to establish the influence frequency band.

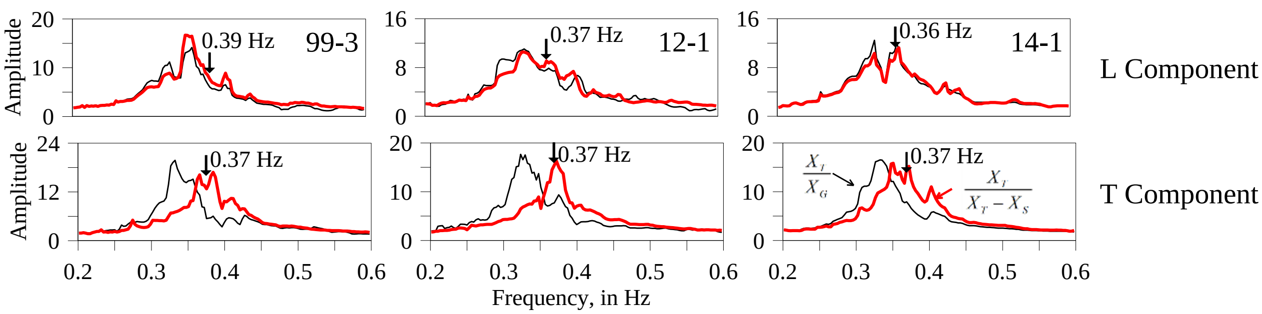

Fig. 3 – Fixed-base (RF_S) and system (RF_{System}) spectral ratios

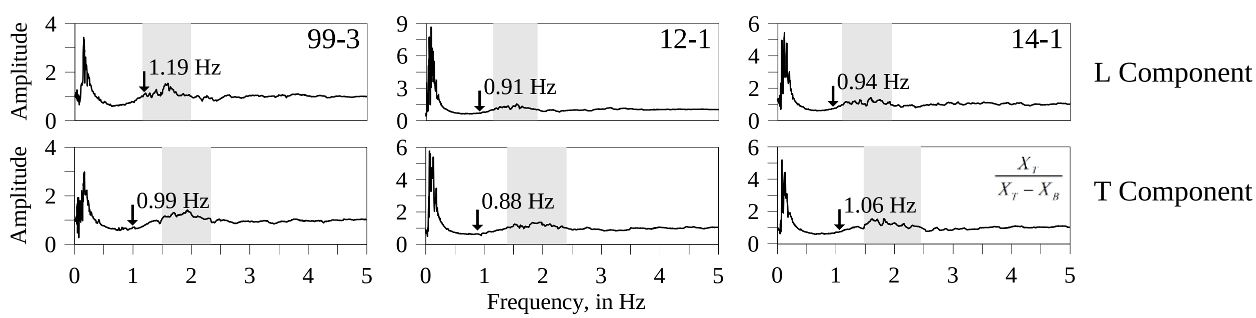

Fig. 4 – Translation base (RF_B) spectral ratios

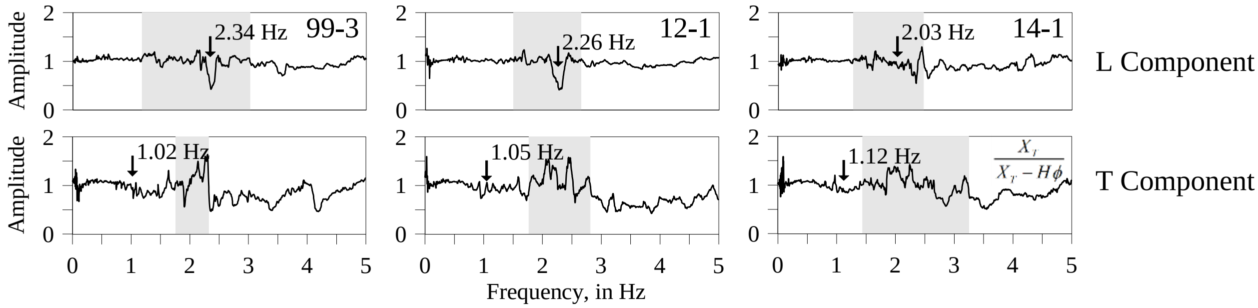

Fig. 5 – Rocking (RF_R) spectral ratios

3.2 MM Method

In order to understand the time variation of the frequencies of the soil-structure system, data was also analyzed with the modal minimization method implemented in system identification software using multiple input and multiple output signals [8]. Time variation of the frequencies was assessed by dividing the records in time windows of 10 to 20 s, similarly to the identification of system frequencies.

Three different models were used to determine the frequencies according to Eqs. 6 to 8 (Fig. 6). 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_L, R_T and R_R). Results are shown in Figs. 7 and 8 (empty square), and a summary of the frequencies of the fix-based structure from the most significant seismic records is presented in Table 7.

Regarding the model used for estimating the horizontal translation frequencies in the L and T components, the input motions are the records at the basement plus the correspondent contribution of structure deformation (E_{BL} and E_{BT}). For the rocking frequencies model in the L and T components, the input motions are the sum of the correspondent contributions of structure deformation and of rocking (E_{CL} and E_{CT}). In both cases the output motions are the responses at the roof relative to its own input motion according to the model and component (R_{BL} and R_{BT} or R_{CL} and R_{CT}) (Fig. 6). Signals were filtered in order to avoid the influence of the fundamental frequencies and, to allow the identification of the horizontal translation and rocking frequencies.

Figs. 7 and 8 show accelerograms recorded at the roof of the buildings in each component. The second graphic, shows the frequencies estimated with MM method (empty squares) for fixed-base conditions. For comparison purposes, this graphic also includes the values obtained with SIM method with the whole record (discontinuous line), SIM method applied in a moving window analysis (solid triangles), and the identified value in the structure spectral ratio RF_S (shaded regions). Last graphics show the identified frequencies related to the horizontal translation and rocking motions of the base. Empty circles represent the values obtained with MM method, whilst solid triangles are those obtained from SIM method. For the first one, the size of the circles is related to the participation factor of the identified frequencies in the filtered responses. Shaded regions are the frequencies identified in the spectral ratios, RF_B and RF_R, in Figs. 4 and 5.

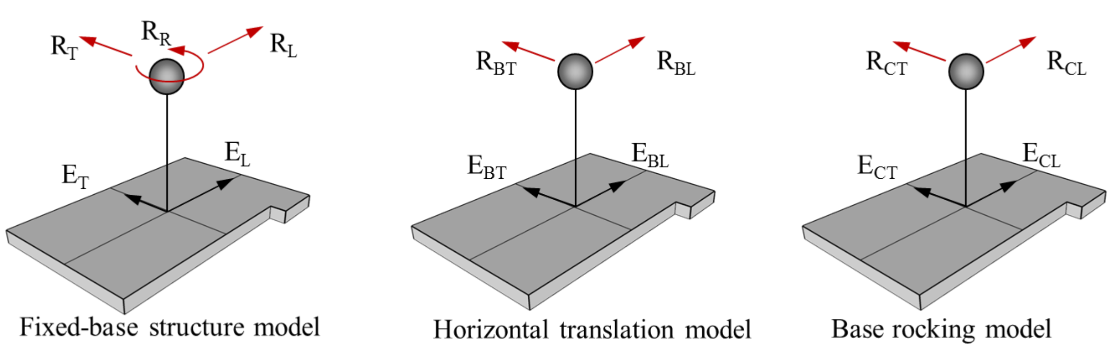

Fig. 6 –Models for MM method

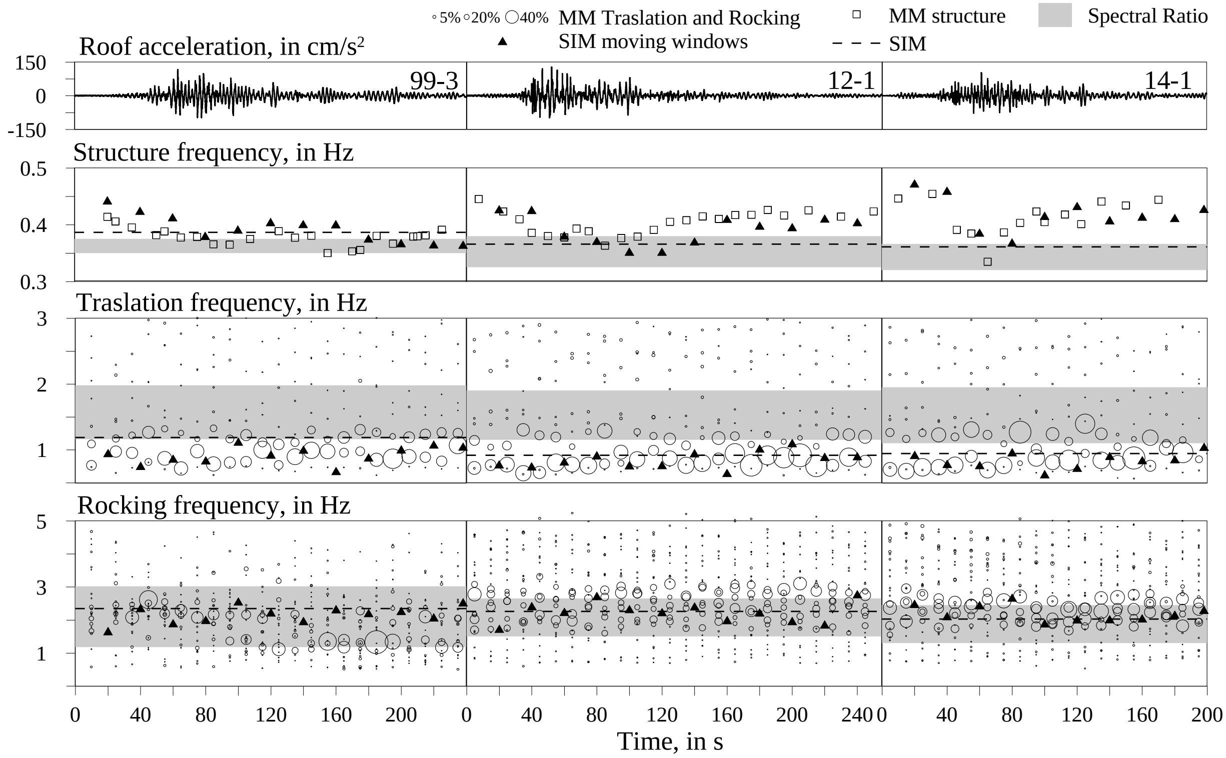

Fig. 7 – Identified and estimated frequencies for the building in L component

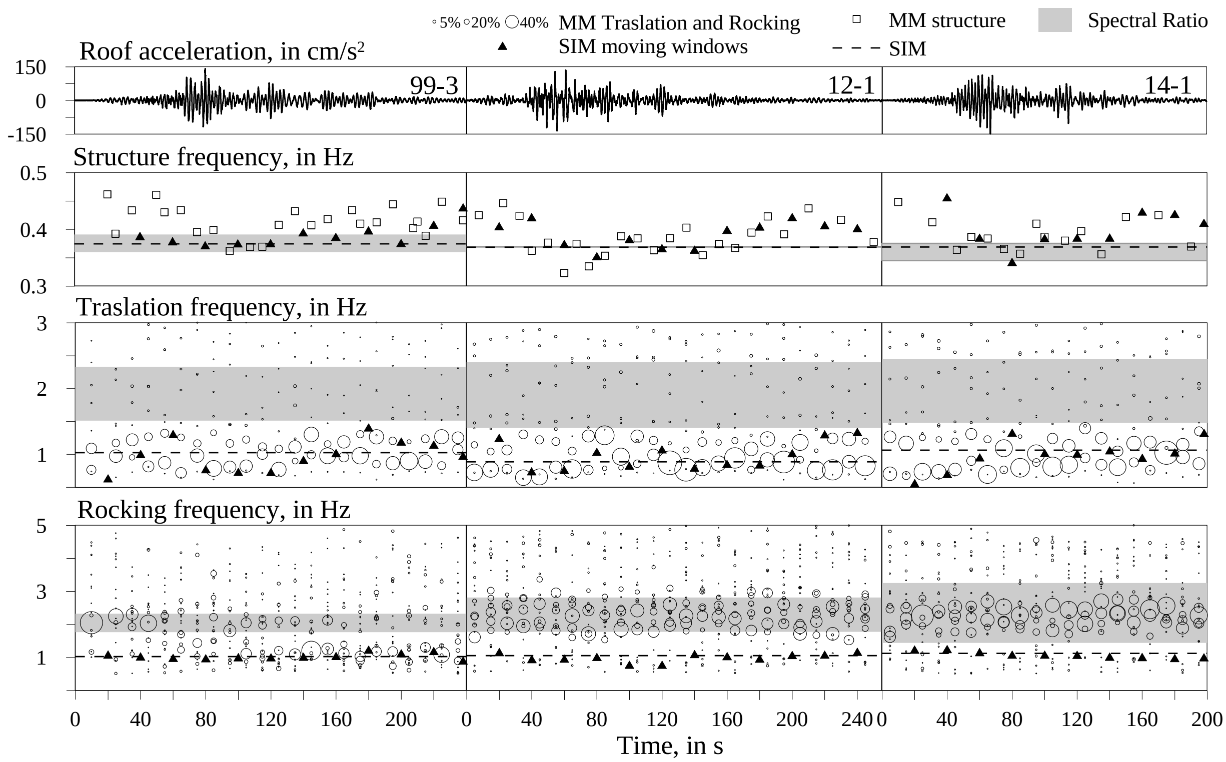

Fig. 8 – Identified and estimated frequencies for the building in T component

Table 7 – Summary of the variation frequencies of the fix-based structure from the most significant seismic records

Event	Component L			Component T		
	f_i	f_s	f_f	f_i	f_s	f_f
99-3	0.410	0.351	0.369	0.424	0.388	0.412
12-1	0.435	0.363	0.422	0.421	0.344	0.417
14-1	0.455	0.335	0.439	0.391	0.352	0.393

f_i - frequency of initial phase, f_s - frequency of intense phase, f_f - frequency of final phase (in Hz)

3.3 Discussion and comparisons

Results in Tables 3, 6 and 7 and Figs. 2, 7 and 8 show 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 MM methods leads to similar results. It must be noticed that the major reductions on these frequencies occurred during the intense phase of the events.

An overall view shows that the values of the translation and rocking frequencies in L component and the translation frequencies in T component do not show significant changes between the values of 1999 events and events 12-1 and 14-1. Also they do not show a clear tendency, neither from the SIM nor from the MM method, similar to that observed in other two buildings in Mexico [12, 13]. This indicates that the variations of the system frequency cannot be clearly related with the variations of the horizontal translation and rocking frequencies, thus suggesting that sources of non-linearity detected in the systems are mainly due to the structure.

Results from models of the MM method show several participating frequencies and vary 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. biggest circles) do not match well with the values estimated with the SIM method.

5. Final comments

The soil consolidation process in Mexico City causes a regional subsidence and an increase in the site dominant frequency. These changes present implications in the dynamic response of the buildings. While the fundamental frequencies of the structure were quasi-resonant with the dominant site frequency in 1990, nowadays, the difference between the fundamental frequencies of the building and the dominant frequencies of the soil is larger. This explains why interstory drifts are smaller during the most intense seismic records in 2014 compared to the 1995 event, where the interstory drift was the largest.

Other consequences of soil consolidation are the changes in the effects of soil-structure interaction (SSI) on the building. For example, in 1990 the piles of the building were supported on the hard stratum and, since then, the building emerged 882 mm with respect to the street-level. Since 1999, with the improvement of the building´s instrumentation, it was possible to study the SSI effects. Performed analyses show that fixed-base and soil-structure system frequencies present similar amplitude-dependence on the input motion. In the L and T component, no evidence of clear changes of horizontal translation or rocking frequencies was found.

Results of a simplified model (SIM) and analysis from different spectral ratios are compared with a system identification method (MM) to estimate the frequencies of buildings and their components of movement. It was found that MM method is useful when estimating the system, fixed-base structure, horizontal translation and rocking frequencies. From both the system and the fixed-base structure models, it was found that the dynamic responses are sensitive to the amplitude of the imposed ground motions. The study revealed that the horizontal translation and rocking movement is associated to several frequencies. Difficulties in identifying this movement were encountered due to the several incident wave sources from the soil.

After the building rehabilitation, main damage was caused by the earthquake on April 25, 1989, just before its instrumentation. This event was of moderate intensity, and the highest one that occurred since then.

The analysis of the seismic records from 1990 to 2015 shows that fundamental vibration frequencies of the building have been reduced up to 12.6% in its horizontal transversal component. In spite of the soil consolidation, the frequency values for moderate intensity events have dropped with respect to the one in 1990. This suggests that the decreasing trend of the values was caused by the effect of damage accumulation in the structural system. The sources of these changes in the dynamic frequencies have been attributed to variations in structural and non-structural elements' properties, soil consolidation, and the change of the piles tip contact presented between 1991 and 1993.

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