Study of Soil-Structure Interaction in Building of 12 Levels in Mexico Using Ambient Vibration

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SUMMARY:

An analysis of Soil Structure Interaction (SSI) effects of a 12 stories building, constructed on based precast elements in northern Baja California region of Mexico, near by the city of Ensenada is here presented. The study was conducted using the regulations stated in the Manual of Technical Procedures of Mexico City Federal District (NTCDF by its acronym in Spanish) and using results obtained from soil-site characterization study in which a model of the site characterization was estimated using ambient vibration measurements.

Keywords: soil-structure interaction, building, ambient vibration

1. INTRODUCTION

Buildings structural response upon external dynamic loads, like those produced by earthquakes, depends on the characteristics of regional earth structure/source, the adjacent soil/site properties and building structure itself (Chen y Scawthorn, 2003). The ground motions are amplified in a significantly way for the structure vibration, such that the accelerations may be several times larger than those of the free-field (Bazán and Meli, 2002).

The structural analysis is performed assuming that the motion is applied at the base and that the forces distributions at higher level of the structure are independent from the foundation. In some cases, however, the movement in any point of the boundary soil-structure is sensitively different, which may occur at that point if the structure were not there; this case is named soil-structure interaction (Bazán and Meli, 2002). The SSI effect is widely evident and normally considered helpful to the structural system under earthquake loads (Khalil et al., 2007), because it is associated with the dynamic behavior of the structure, and may be seen as an increment of the fundamental period as well as an increment on the structure damping in comparison with fixed base systems (García, 2006). It is known that the SSI reduce the stresses in structures, hence normally disregard the SSI leads to a conservative project (Espinoza, 1999). In some cases the SSI effect is adverse due to an increase in the separation of adjacent building. Recent studies and post seismic observation suggested that SSI can be damaging for the structure and foundation, especially for structure in soft-soil (Khalil et al., 2007).

2. SITE RESPONSE

In this study, the soil response analysis was conducted by means of using ambient vibration (micro-tremors), consisting of very small amplitude waves with periods between 0.1 and 10 s (Architectural Institute of Japan, 1993). Ambient vibration is normally generated by human activity, factory operation and road traffic (Kanai y Tanaka, 1961). In addition to the above, there are also vibrations produced by the wind, which are introduced to the ground by the trees, as well as by hills or topographic features, (Seo, 1995). The source of this energy is not associated with earthquakes and some studies consider that noise has a natural origin and is composed of surface waves generated in zones of ocean-continent interaction, the vibration fundamental mode of the earth, changes in atmospheric pressure and volcanic activity in addition of the mentioned above (Espinoza, 2002).

The use of ambient vibration for the estimation of dynamic characteristic of soils was widely driven by the Nakamura technique (Nakamura, 1989) which provides a powerfully tool for the characterization of local site response of soft soils and his respective resonance frequencies. The technique has proven to be cheaper and convenient to estimate reliably the predominant frequency of the soil. Moreover its use has been controversial, but mostly thinks that technique is efficient to determinate the predominant period of the soil but doesn't identify amplification factors (Bard, 1997).

Nakamura proposed that with ambient vibration spectral ratios of horizontal (H) and vertical (V) components (HVSR) of ground motion it is possible to estimate the fundamental vibration frequency of the soil (Aguirre et al., 2003). In addition to the above, other method that uses ambient vibration measurements is the SPAC (SPatial Auto-Correlation), which is mainly used to estimate the earth shallow structure (soil layer system) of the site (Tapia, 2009).

3. FIELD DATA COLLECTION

We recorded simultaneously ambient vibration time series of up to 16 minutes in different size triangular arrays, which allows doing the analysis of temporary variability to identify possible effects on the dominant frequency of the site. Exploiting the information of the soil dominant frequency, which is estimated with Nakamura Method, it is then possible to identify and choose the site dominant frequency which is statistically more representative and reliable. Five different size triangular arrays were used for the purpose described above. The sensors were located: one in the center of an equilateral triangle and the remaining three were moving to cover each of the edges of the five triangles of 2.5, 5.0, 10.0, 15.0 and 20.0 meters of radial distance.

The sensors recorded the three directions of the ground motion (*x*, *y*, and *z*). Noted that channel numbers denotes: (i) 4 for the west direction (*H2*); (ii) 3 for the north direction (*H1*) and (iii) 1, 2, 5 and 6 for vertical direction (*V*), keeping this configuration for all five arrays. Four triaxal Epi-Sensor accelerometers Model FBA ES-T from Kinemetrics were used in the free-field to perform the measurements, connected to a data acquisition system supporting up to 6 channels. Once placed and leveled the 4 sensors; one in the center, and the 3 on the remaining vertexes of the triangle, we recorded simultaneously time series of 16 minutes of ambient vibration at sampling frequency of 100 Hz.

For SPAC array, in which the sensors were connected with a directional interface, whose function is to direct the channels towards the recorder, (it works as a selector and only the desired channels/components are recorded), where the data is stored in binary format. Finally the data is transferred to a computer for further format change, processing and analysis.

4. SOIL FUNDAMENTAL PERIOD

To estimate the soil fundamental period we proceeded as follow: (i) first, a seasonal analysis is performed, and estimated 9 HVSR from time series of 9849 data points of length, with overlap of 75 % of 1024 data point segments to calculate spectrums in the 5 and 20 meters cases respectively. The most stable seasonal variability were obtained to 4 time-windows of 18177 data points, and (ii) second, Fourier spectrums were calculated on each of the records obtained to use in the HVSR on each record from Fouries Spectrum.

With spectral ratios H2/V and the recording time on each array (5 and 20 meter) a 0.39 Hz soil predominant frequency that belongs to period of 2.56 sec and for spectral ratios H1/V the value of 0.20 Hz belongs to a period of 5 sec. Because it has greater consistency, the spectral ratio H2/V, the soil predominant period in the present work is 2.56 sec.

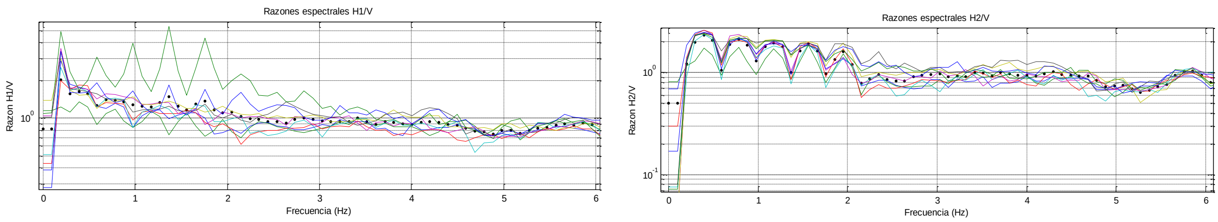

Figure 1. Spectral ratio (H1/V left and H2/V right) from 5 m SPAC array.

5. RELEVANCE FROM STRUCTURE-SOIL INTERACTION.

The analysis of the building near by the city of Ensenada, México evaluates the dynamic response of the structure on fixed base and taking into account the SSI effect, considering the structure in soft soil. The NTCDF, establishes the equation 5.1 that do not consider the SSI effect.

$$\frac{P_e H_s}{P_s H_e} > 2.5 \qquad (5.1)$$

where:
H_s: depth of solid deposits on the site of interest.
H_e: effective height of the vibrating structure in its fundamental mode.
P_e: fundamental period of the assumed structure with fixed base.
P_s: longer dominant period of the ground at the site of interest

The depth of solid deposits (*Hs*) can be estimated from the following empirical correlation (Avilés y Pérez-Rocha, 2004):

$$H_s = 31\sqrt{P_s - 0.5} \qquad (5.2)$$

To determine the effective height of the vibrating structure in its fundamental mode (I) uses the following formula taken from the standards mentioned above:

$$H_e = \frac{\sum W_i z_{ij} h_i}{\sum W_i z_{ij}} \qquad (5.3)$$

where:
z_{ij} = is the modal displacement amplitude of the i-th foundation embedment.
W_i = is the mass of the i-th foundation embedment.
h_i = is the height of the i-th foundation embedment.

Performed the study of environmental vibration, the dominant ground period is *Ps* = 2.56 s, the period of the structure with fixed base is *Pe* = 1.73 s which was calculated with the modal analysis, the depth of solid deposits *Hs* = 44.49 m and the effective height of the structure vibrating in its fundamental mode I = 42.68 m from the equation 5.2 and 5.3 respectively. Using these values and substituting in equation 5.1, the obtained result was equation 5.4: the effect of soil-structure interaction must be considered.

$$\frac{P_e H_s}{P_s H_e} = 0.70 \qquad (5.4)$$

5.1 Dynamic Analysis

Using SAP2000 software and performing a preliminary modal analysis, different modes of vibration of the structure at the directions *X* and *Y* were estimated (see Table 5.1).

Table 5.1. Vibration Period (*P*) of the structure

Vibration mode	Period (s)	Direction	Vibration mode	Period (s)	Direction
1	1.73	*X*	6	0.33	*X*
2	1.44	*Y*	7	0.26	*X*
3	0.88	Rotation	8	0.21	*Y*
4	0.52	*X*	9	0.20	*Y*
5	0.39	*Y*			

The following figure shows the results of modal analysis, the modal displacement of story in both directions and the modal configurations in *X* and *Y*, satisfying the NTCDF (2004) in the sense of including at least three modes in each direction. The modal displacements of story are taken in the center of mass of the structure under study.

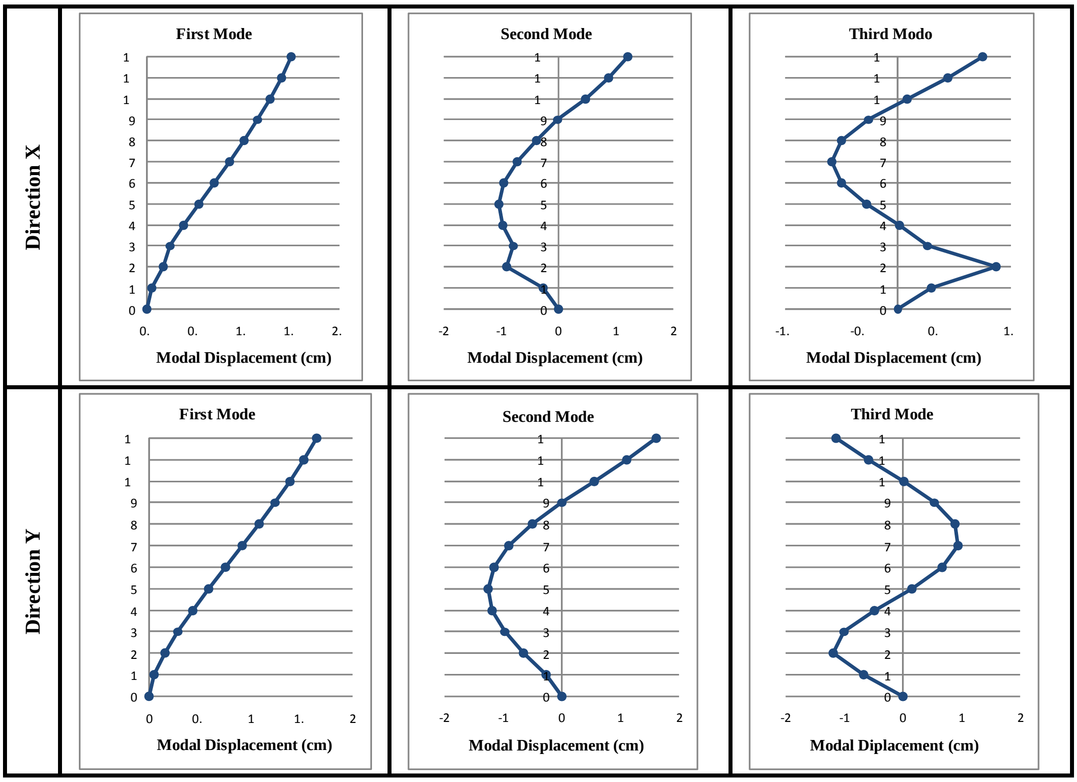

Figure 2. Modal configurations of the main modes of vibration in both directions

Chapter 9 of the NTCDF (2004), states that the sum of the weights in each direction of analysis must be greater than or equal to 90 % by weight. In the structure analyzed, the overall weight in the *X*-direction was 95.94% and the actual weight in the *Y*-direction was 94.59% which is acceptable according to later estimates (see Table 5.2).

Table 5.2. Effective modal weights and total weight of the structure in each direction of analysis

Direction	***X***	***Y***
Effective modal weights (MPa-s²/cm)	0.071	0.070
total weight of the structure (MPa -s²/cm)	0.074	0.074
Effective modal weight (%)	95.94	94.59

Knowing the mode *Zj* in any scale, generalized masses are determined. For orthonormal mode *Zj* is divided by $Z\sqrt{m_j^*}$ and modal participation coefficients are calculated (see Table 5.3).

Table 5.3. Generalized mass and modal participation factors of the three modes in each direction mass

Mode number	Generalize Mass m_j^*		Modal participation fcators p_j	
	Direction *X*	Direction *Y*	Direction *X*	Direction *Y*
First	4.24	4.96	2.08	2.07
Second	4.02	5.07	-1.51	-1.33
Third	4.11	4.79	0.84	-1.09

Chapter 3 of the NTCDF (2004) describes the design seismic intensity with smoothed spectra that provide the maximum pseudo-acceleration A_j, for each period P_j.

The building belongs to the group B, that was built in zone II and applies a reduction factor for seismic $Q = 2$. From these data, spectral accelerations were determined for each of the modes according to the NTCDF (2004).

Table 5.4. Parameter values to calculate the acceleration spectrum

Zone	c	a_0	P_a	P_b	r
II	0.32	0.08	0.20 s	1.35 s	1.33

The displacements corresponding to each of the modes are calculated by multiplying the shear stiffness matrix by displacement. The total maximum response modes (*U* displacement, relative displacement δU and shear *V*) are obtained with the results shown in the directions *X* and *Y*.

Finally, the total and relative displacement inter-story will be obtained from the analysis with reduced seismic forces, according to the criteria set out in Chapter 4 of the NTCDF (2004), by multiplying with the seismic behavior factor of $Q = 2$.

6. STORY DRIFTS

Table 6.1 shows the story drifts, which are obtained by dividing the relative displacement of each level by the height thereof. Also shown, are the percentages of story drifts determining the difference story drifts and maximum story drifts allowable of 0.012.

Table 6.1. Story drifts in both directions for the structure.

Story	Story drift whit fixed base							
	SAP2000		Modal Analysis		SAP2000		Modal Analysis	
	Direction *X*	Direction *Y*	Direction *X*	Direction *Y*	Direction *X* (%)	Direction *Y* (%)	Direction *X* (%)	Direction *Y* (%)
1	0.003	0.002	0.003	0.002	75	85	78	85
2	0.008	0.004	0.007	0.004	36	67	38	69
3	0.004	0.005	0.004	0.005	63	58	66	58
4	0.009	0.006	0.009	0.006	25	50	25	52
5	0.010	0.006	0.010	0.006	20	47	19	47
6	0.010	0.007	0.010	0.007	18	46	17	46
7	0.010	0.006	0.010	0.007	19	47	18	45
8	0.009	0.006	0.010	0.006	22	48	20	46
9	0.009	0.006	0.009	0.006	28	51	25	49
10	0.008	0.005	0.008	0.006	33	55	31	51
11	0.007	0.005	0.007	0.005	39	58	38	54
12	0.007	0.005	0.006	0.005	45	61	47	58

7. ANALYSIS CONSIDERING THE EFFECT OF SOIL-STRUCTURE INTERACTION.

7.1 Soil-Structure System.

For design purposes, the effect of soil-structure interaction is often considered only in the fundamental vibration mode. The contribution of higher modes is determined as provided for structures without interaction. If the structure of various degrees of freedom responds essentially as a basic oscillator and if the stratified soil deposit basically behaves as a homogeneous mantle, the soil-structure can be represented as established by Aviles and Perez Rocha, where the structure is characterized by its: height (H_e), mass (M_e), damping (ζ_e), and period (T_e). The foundation is defined by its radius (R), foundation embedment (D), mass (M_c) and moment of inertia (J_c) about its horizontal centroidal axis. Finally, the layer is characterized by its thickness (H_s), Poisson's ratio (v_s), period (T_s), shear wave velocity (V_s), and damping (ζ_s).

The horizontal displacement of the ground surface generated by the free-field motion is denoted by $\ddot{X}_g$. However, the presence of the foundation modifies the motion of the free-field ground motion. This results in a movement into the foundation component consisting of horizontal translation and rotation in a vertical plane, denoted by Xc and Φc, respectively. The degrees of freedom of the foundation-structure system produce the relative displacement of the structure X_e.

8. CORRECTED MODAL RESPONSE ANALYSIS FOR THE EFFECT OF SOIL-STRUCTURE INTERACTION.

In order to take into account the effects of dynamic soil-structure interaction we used the specifications of the NTCDF (2004). These specifications are based on simplified models that idealize the structure as a simple oscillator and the ground like a soft blanket resting on a non-deformable semi-space (Avilés and Pérez-Rocha, 2004).

8.1 Period

The effective period of the structure $\tilde{P}_e$ considering the effect of soil-structure interaction is determined according to the following equation:

$$\widetilde{P}_e = \sqrt{P_e^2 + P_x^2 + P_r^2} \tag{8.1}$$

Where P_e is the fundamental period assuming rigid base in the direction being analyzed, P_x and P_r are the natural periods that would have if it were infinite rigid structure and its base could only move or rotate respectively.

Table 8.1 shows both directions of fundamental periods of the assumed structure with fixed base, as P_x and P_r periods, and also the effective period $\widetilde{P}_e$. There is an increase of 1.7% in the *X*-direction and 2.1% in the *Y*-direction.

Table 8.1. Periods *Pe*, *Px*, *Pr* of the system considering the effect of soil-structure interaction.

Period	Direction *X*	Direction *Y*
P_e	1.73 s	1.44 s
P_x	0.06 s	0.06 s
P_r	0.30 s	0.31 s
$\widetilde{P}_e$	1.76 s	1.47 s

8.2 Damping

The effective damping of the structure considering the effect of soil-structure interaction is determined according to the following equation:

$$\xi_e = \zeta_e \left(\frac{p_e}{\widetilde{p}_e} \right)^2 + \frac{\zeta_x}{1 + 2\zeta_x^2} \left(\frac{p_x}{\widetilde{p}_e} \right)^2 + \frac{\zeta_r}{1 + 2\zeta_r^2} \left(\frac{p_r}{\widetilde{p}_e} \right)^2 \tag{8.2}$$

Where ζ_e is the fraction of critical damping of the assumed structure based un-deformable, ζ_x and ζ_r the soil damping coefficients in the translational and rotational modes, respectively.

In table 8.2, damping values of the structure for both directions are provided, assuming it is resting on a rigid base. The soil relative damping coefficients (ζ_x), (ζ_r), are also provided, as well as the effective damping (ξ_e). There is a reduction of 2% in the *X*-direction and 4% in *Y*-direction.

Table 8.2. Damping ζ_e, ζ_x ζ_r, and ξ_e of the system considering the effect of soil structure.

Damping	Direction X	Directionn Y
ζ_e	0.050	0.050
ζ_x	0.044	0.047
ζ_r	0.028	0.019
ξ_e	0.049	0.048

8.3 Lateral Displacement

Lateral displacements of the structure in the analyzed direction corrected by SSI, are determined by the expression:

$$\tilde{X}_l = \frac{\tilde{V}_o}{V_o}\left[X_i + (h_i + D)\frac{M_o}{K_r}\right] \tag{8.3}$$

Being factor $\frac{\tilde{V}_o}{V_o}$ = 1.25 for the lateral displacement modified by interaction in both directions, X_i is the lateral displacement of *i-th* level of the structure with fixed base multiplied by the seismic behavior factor $Q = 2$, h_i is the height of the story, D is foundation embedment equal to 2 m for both directions, Kr = 651652.277 MPa-m, and 568891.960 MPa-m for *X*- and *Y*-directions, respectively, and the overturning moment is: $Mo = V_j\ (H_i + D)$, where H_i is the height of the story to the base of the foundation and V_j is the shear in the direction of analysis.

9. STORY DRIFTS

Table 9.1 shows the story drifts obtained by dividing the relative shift of each level of the height thereof. Also are shown the percentages of story drifts determining the difference in story drifts and maximum story drifts allowable 0.015.

Table 9.1. Story drifts in both directions to structure considering SSI effect.

Story	Story Drifts considering SSI effect							
	SAP2000		NTCDF		SAP2000		NTCDF	
	Direction *X*	Direction *Y*	Direction *X*	Direction *Y*	Direction *X* (%)	Direction *Y* (%)	Direction *X* (%)	Direction *Y* (%)
1	0.007	0.004	0.007	0.005	54	74	56	69
2	0.016	0.008	0.019	0.009	-10	45	-26	38
3	0.009	0.011	0.010	0.013	42	30	33	16
4	0.019	0.013	0.023	0.015	-25	16	-51	2
5	0.020	0.013	0.025	0.016	-33	11	-64	-6
6	0.020	0.014	0.025	0.017	-35	9	-68	-10
7	0.020	0.014	0.025	0.017	-33	10	-65	-11
8	0.019	0.013	0.025	0.016	-29	13	-65	-9
9	0.018	0.012	0.023	0.016	-18	17	-50	-5
10	0.016	0.012	0.021	0.015	-10	22	-42	0
11	0.015	0.011	0.019	0.014	-2	28	-28	6
12	0.014	0.010	0.017	0.013	9	33	-10	12

10. RESULTS COMPARISON

10.1 Story Drifts considering fixed base.

Figure 10.1 shows the story drifts in *X* and *Y* which are shown as ratios of relative displacements between the height of the level and the maximum allowable ratio according to the NTCDF (2004). The relative displacements using modal analysis computed with the software SAP2000 were obtained for the center of mass of each story.

Story drifts (figure 10.1) are between 0.006 and 0.012, maximum allowed by regulation (section 1.8 of NTCDF, 2004). The limit of 0.012 is used when there are elements capable of supporting appreciable deformation or as the rules when there are no masonry walls or they are not linked to the main structure.

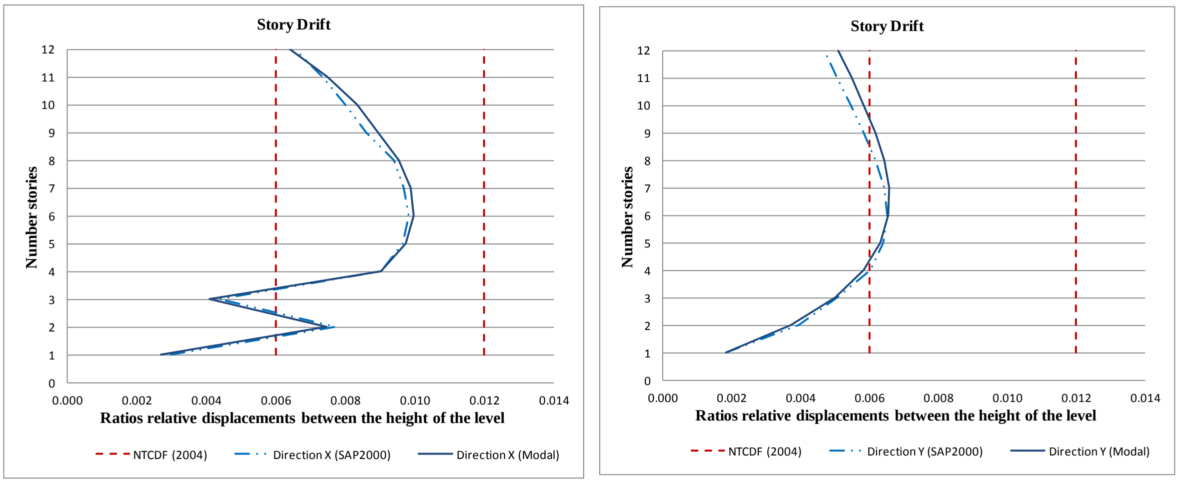

Figure 10.1. Story drifts in *X* and *Y* direction considering fixed base of the building (Diaz, 2009)**.**

11. CONCLUSIONS

Using data from the studied building and the results of environmental vibration in the soil, we found that the SSI effect is relevant, and should be considered in the seismic analysis of this building.

Performing the fixed base analysis, identified the fundamental period of structure equal to 1.73 s and 1.44 s in the *X* and *Y*, respectively, and considered a damping equal to 0.05, we found that there were story drifts greater than 0.006 in both directions.

Performing the analysis considering the soil-structure interaction effect, which is influenced by the dynamic behavior of the structure, there was an increase in the fundamental period of 1.7% and 2.1% in the *X* and *Y* respectively, and a decrease in damping by 2% for the *X*-direction and 4% for the *Y*-direction compared to the fixed base model. Larger distortions were also obtained exceeding the maximum value of 0015 in the *X*-direction.

The drifts in codes are higher than those obtained with SAP2000 by a factor of 1.25. Rigidization of the structure in both directions and in a greater extent in the *X*-direction is recomended. The above can be achieve by changing the columns section, placing additional shear walls or brace where required by the structure.

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