Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Soil-structure interaction effects in a building

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ABSTRACT: This study presents an analysis of the dynamic behavior of an instrumented building located on soft soil in México City. Several earthquakes originated in different epicentral regions were considered. For this type of structure the flexibility of the soil can decrease the frequency of the fixed base model up to four times. The damping capacity of the soil-structure system is very high, with an equivalent damping ratio up to 0.31. Based on the observed response of the building, the importance of taking into account this phenomenon in the dynamic response analysis of the building is evident.

1 INTRODUCTION

With the purpose of analysis the structural behavior under seismic actions in recent years, some Mexican institutions have instrumented several buildings located on soft soil. One of the most important points in the analysis of these structures is to define the soil-structure interaction effects on the structural response.

In this work, the dynamic response of a three-story building founded on soft soil, is analyzed under the effect of five seismic events which occurred between 1987 and 1990.

The structural characteristics of this building and the high soil flexibility gives an exceptional opportunity to study the soil-structure interaction phenomenon.

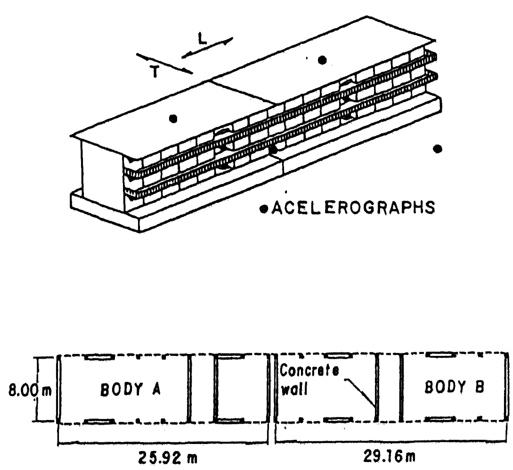

Figure 1. Isometric view and typical floor plan of the building.

2 BUILDING

The building has three stories and its structural system is based on steel frames in both directions; the columns are embedded in reinforced concrete. Several 15 cm thick concrete walls are placed in the two main directions of the structure (Figure 1).

The floor system is a 10 cm thick concrete flat slab supported by steel beams. The building has two bodies (A and B), separated by a 10 cm wide construction joint. Body A measures 8 by 26 m in plan and body B 8 by 29 m, with a story height of 3.5 m for both bodies. Each body is supported on a concrete box foundation placed 2.50 m below the ground level.

The fundamental frequency of the site where the structure is located is about 0.43 Hz. The soil profile is characterized by a 4 m thick surface layer with a shear wave velocity of 100 m/s (Jaime, Romo & Ovando 1987); below this level, the shear wave velocity presents a mean value of 60 m/s until the hard layer is found (at 40 m depth).

3 DYNAMIC CHARACTERISTICS

The natural frequencies of the structure were obtained using ambient vibration and pull-back tests (Murià-Vila, González & Sánchez 1987). Tests were carried out in three stages: the first two were the ambient vibration measurements (one of them made during the day and the other one at night); and the last one the pull-back test.

Due to the high flexibility of the soil the results of the experiments during the day basically reflected the surface waves of the surrounding soil. Therefore, the identification of the dynamic characteristics of the system, mainly in the transverse direction (T), was very difficult. At night, when the ambient noise decreased, the fundamental frequencies of the torsional vibration (R) and the longitudinal direction (L) were corroborated. The fundamental frequencie of the direction T was detected with the pull-back test (Table 1).

The equivalent damping ratio associated to the fundamental modes for directions T and L

Table 1. Natural frequencies of the building.

	Body A			Body B		
	T	L	R	T	L	R
A1	2.4-3.8	4.3-4.9	5.6-6.4	2.3-3.5	4.4-4.9	6.0-6.3
A2	2.9-3.8	4.3-4.5	6.2-6.4	--	--	--
P	--	--	--	2.90	4.30	5.8-6.2
MF	--	--	--	2.55	3.36	--
MR	--	--	--	10.04	7.99	--

A1 - ambient vibration test during the day
A2 - ambient vibration test at night
P - pull-back test
MF - analytical model of body B, flexible base
MR - analytical model of body B, rigid base

Table 2. Critical damping ratios calculated from pull-back test.

T	L	R
0.22-0.31	0.06-0.08	0.05-0.12

of the soil-structure system are presented in Table 2. The equivalent damping ratios obtained were in the range 0.05-0.31, which are larger than those estimated in ambient vibration measurements of massive structures in Mexico City situated on hard soil, with damping ratios smaller than 0.02 (Murià-Vila 1991).

4 RECORDED EARTHQUAKE RESPONSE

The building is instrumented with three triaxial accelerographs and one more placed near to the structure on the ground (Figure 1). The accelerographs are interconnected and triggered by the ground accelerograph.

At present, six earthquakes have been registered, which occurred in different epicentral regions of the country. The accelerograms recorded during each earthquake at the ground and roof of the body B and the corresponding Fourier spectra are shown in Figure 2. Their principal characteristics are summarized in Table 3. The maximum accelerations correspond to earthquake B and were 62 and 54 cm/s^2 at the roof of the bodies A and B, respectively, in direction T. Unfortunately, the ground and ground floor accelerographs failed to function.

The spectral shapes are different between one earthquake and another. In the stronger earthquake (B), the maximum peak is associated basically with the natural frequency of the site (0.44-0.46 Hz).

Table 3. Principal characteristics of accelerograms recorded.

Record	Date D -M -Y	G.M.T. time h :m :s	Mc	Epicentral distance [km]	Focal depth [km]	Strike	Component	Maximun aceleration [cm/s^2] Ground	Body A	Body B	Record duration [s]
A	08-02-88	13:52:57	5.1	354	33	S41.85W	V T L	1.7 4.5 4.3	--- --- ---	2.6 6.5 5.7	72
B	25-04-89	14:29:01	6.5	293	21	S01.11E	V T L	--- --- ---	9.2 62.3 48.5	16.6 53.5 51.0	275
C	2-05-89	09:30:18	5.1	323	19	S08.25W	V T L	2.0 4.6 5.2	2.0 5.5 7.0	1.9 5.8 6.2	72
D	12-08-89	15:31:50	4.8	214	33	S54.25W	V T L	0.9 2.0 1.4	1.2 2.5 2.4	1.1 2.4 2.0	20
E	11-05-90	23:43:51	5.3	320	15	S34.78W	V T L	1.5 4.2 2.8	1.6 4.3 4.2	1.5 3.6 3.6	53
F	31-05-90	07:35:29	5.5	323	34	S34.29W	V T L	2.1 9.2 5.6	--- --- ---	2.9 9.0 8.1	102

V - vertical component, T - transversal component (NS), L - longitudinal component (EW), Mc - Coda magnitude

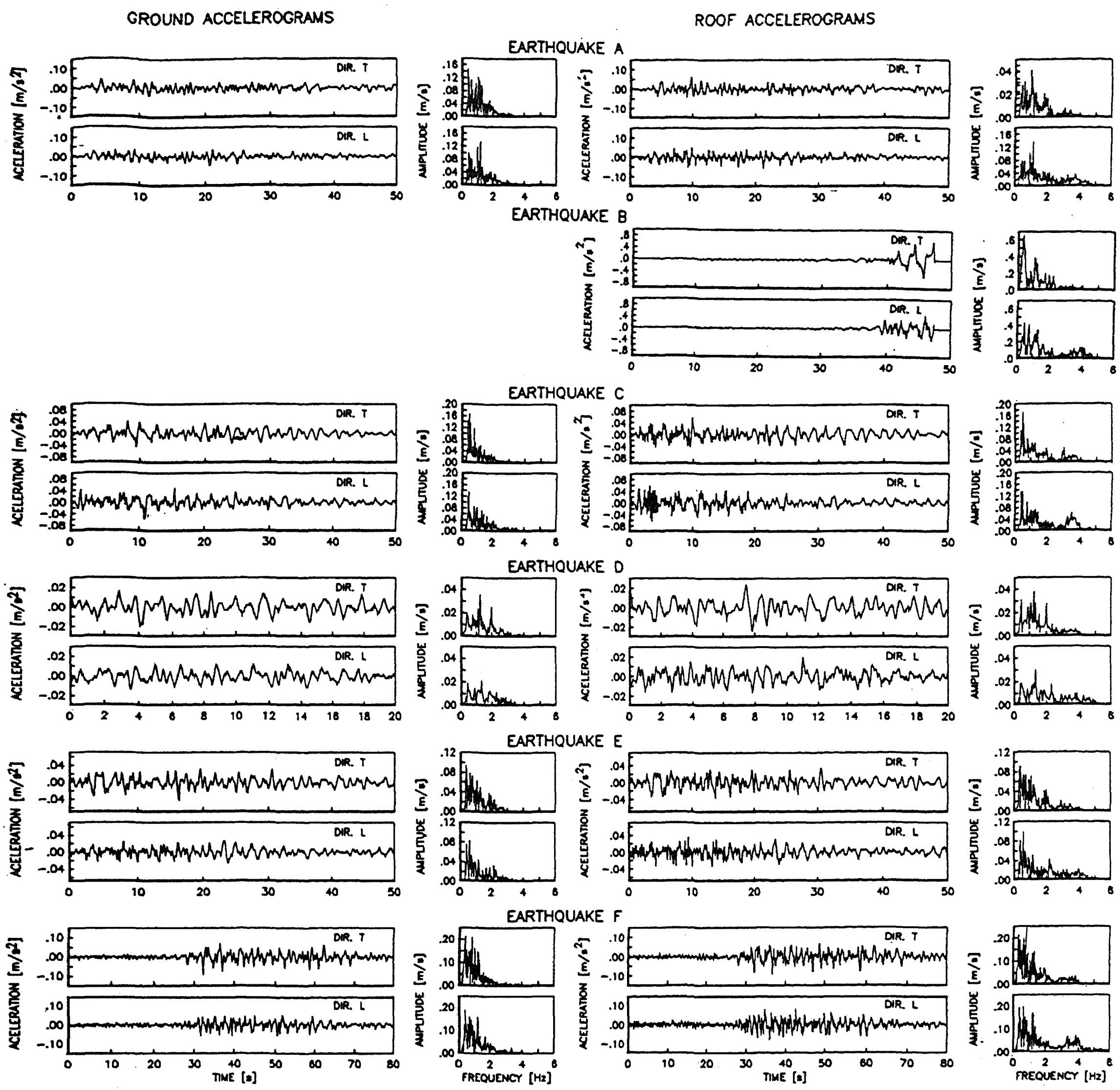

Figure 2. Accelerograms recorded in the building and the corresponding Fourier spectra.

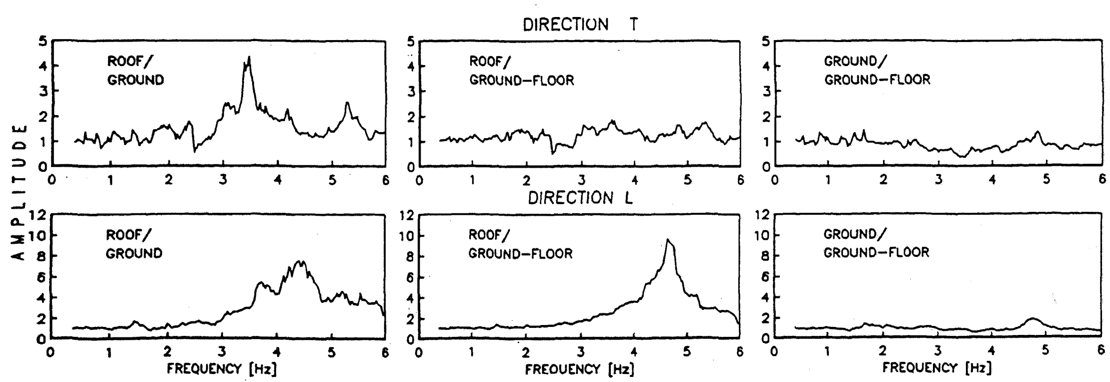

Figure 3. Transfer functions of the accelerograms recorded in the building during earthquake B.

A comparison of the recorded accelerograms reveals the variation of the signal when the movement is transmitted through the structure. This fact is more evident when the Fourier spectra are compared (Figure 2). Due to the fact that the peaks are associated to the natural frequency of the structure, the Fourier spectra of the roof records show a frequency interval (2.5-4.5 Hz) with several spectral peaks that do not appear in the corresponding ground spectra.

Earthquake A was the only seismic event registered by the ground floor accelerograph. The transfer functions calculated in this event are shown in Figure 3; the movements between ground and ground floor are similar, but there are differences between spectral quotients of roof-ground and roof-ground floor in direction T. In the first case, a peak of fundamental frequency is clearly identified, while in the second case the amplitude practically disappears and can be confused with the other. This could be due to the great difference between the stiffness of the structure and the ground; i.e. the soil ground movements cause translation and rotation displacements of the rigid body. This could explain the difficulty to identify the natural frequencies of the structure in that direction. In the two L direction cases, the peak associated to the natural frequency of vibration is defined, but in the second case it is more evident.

When the Fourier spectra of the accelerograms registered on the roof of bodies A and B with different earthquakes are compared, a similarity in direction L among them is found, but not in direction T. This fact is also observed in ambient vibration tests.

5 MATHEMATICAL MODEL

In this work only the analyses of body B model will be described. The structure was conceived as a plane-frame system interconnected by a floor diaphragm infinitely rigid in its plane. In the first part of the analysis, the frequencies and modal shapes of the structure were determined assuming a rigid base. A proportional damping ratio of 0.01 for the first two modes was assumed. This is a typical value for these kind of structures placed on hard soil.

To take into account the soil-structure interaction effects in the system, two degrees of freedom associated to the horizontal translation and to the base rocking of the structure were incorporated. The lateral translation stiffness (K_x), the rocking stiffness (K_R), the lateral damping (C_x) and the rocking damping (C_R) were represented with lumped parameters (Gazetas 1983). The internal damping of the soil, radiation damping, aspect ratio and excitation frequency were considered as well (Dobry 1986).

Figure 4 shows the modal shapes obtained from the models corresponding to the first four modes of vibration in directions T and L, considering fixed and flexible base. Significative differences were found. The correlation between the modal shape corresponding to the fourth mode with flexible base and the second mode of the fixed base model is very high; they have a difference of frequency smaller than five per cent.

The second mode with flexible base is fundamentally associated to a horizontal translation of the base; the third is associated to the rocking movement. Moreover, in the figure appears the frequencies and some values of the fundamental modes experimentally obtained. In direction T these values agree with those calculated for the flexible base models, with differences of 11% in the frequency values; instead, in direction L there are differences up to 28%. The discrepancy in the vibration modes is due, in part, because they are non-normal modes.

Damping coefficient values C_x and C_R of the mathematical model were calculated with two methods: a) using the equations proposed by Dobry and Gazetas (1986) and b) fitting these values in order to obtain critical damping ratios similar to those obtained from the test program. In Table 4 the equivalent damping ratio and the damping coefficients according to the experimental results and the semi-empiric equation are compared: for direction T these values are similar, but for direction L they are very different.

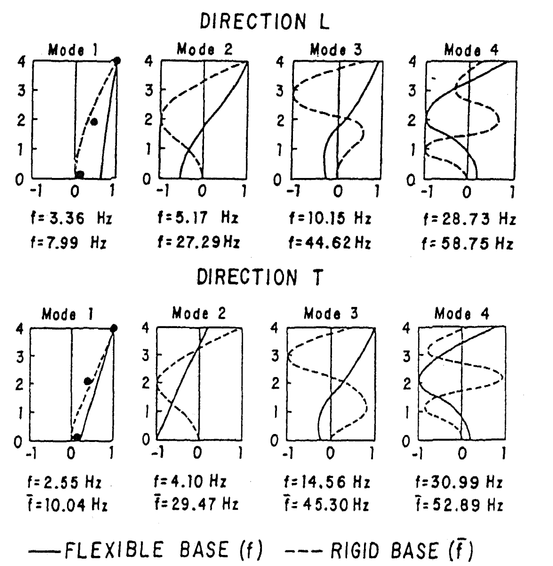

Figure 4. Modes shapes calculated and measured (• experimental values).

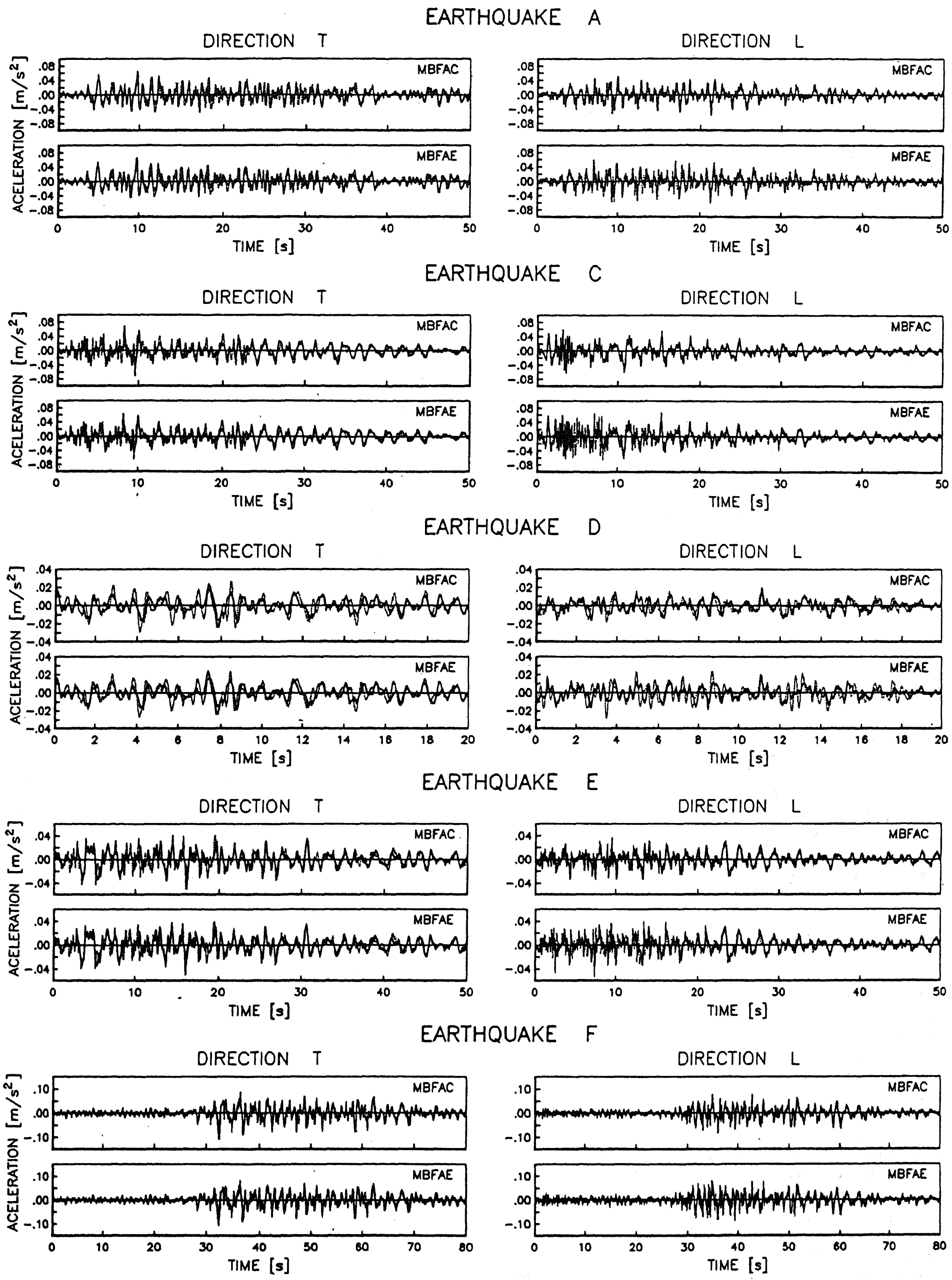

Figure 5. Comparison between calculated (dashed lines) and recorded acceleration responses (solid lines).

Table 4. Comparison of the damping values considered in the analysis.

	Calculated damping		Experimentaly fitted damping	
	T	L	T	L
h	0.16	0.28	0.26	0.07
C_x	5009	4711	8666	989
C_R	27450	161508	47489	33917

h - equivalent critical damping ratio
C_x - lateral damping coefficients [T.s/m]
C_R - rocking damping coefficients [T.m.s/rad]

6 RESPONSE ANALYSIS

A step by step analysis of the structural response was carried out taking into account the calibrated mathematical models with the experimental measurements. For the degrees of freedom associated to the soil-structure interaction, the calculated and the fitted damping coeficients with the experimental values were considered. The analysis was based on the Newmark Beta Method (Newmark 1959).

The ground accelerograms were used as base excitation considering only the horizontal movement in the two directions.

In order to observe the influence of soil-structure interaction on the structural response, three alternatives in each mathematical model were carried out: flexible base model considering an equivalent damping ratio of one per cent (MBFSA), flexible base model with the damping coefficients of the base obtained analytically (MBFAC), and flexible base model with the damping coefficients of the base obtained experimentally (MBFAE).

When the acceleration responses of the alternative MBFSA and the experimental ones are compared, maximum amplitudes differ by as much as three times; this fact showed the importance to consider not only the soil flexibility, but the energy dissipation of the soil.

The analysis shows that in direction L numerical models are not representative of the observed behavior; the coupling between the foundation box of the two bodies and the limitations of the expressions to represent the soil-structure interaction effects in that direction could be the cause of such behavior.

In Figure 5, the experimental and analytical responses of the roof movement for the earthquakes A, C, D, E, and F are compared for the alternatives MBFAC and MBFA. In spite of the differences in the acceleration amplitudes and frequencies, there is a good correlation between the experimental and analytical responses. The correlation is not as good for earthquake D, probably due to the small amplitudes of the movement which were more affected for the resolution in amplitude of the accelerograph.

7 CONCLUSIONS

The fundamental modes of vibration of the soil-structure system analyzed were significantly modified by the soil flexibility. The frequencies calculated with the flexible base model differ up to 3.9 times from that corresponding to a rigid base model.

This study shows the importance of taking into account not only the flexibility of the soil, but the energy dissipating capacity of the soil in order to obtain a good correlation between the analytical and experimental responses. However, it is important to mention that the model response that considers the damping experimentally obtained in the longitudinal direction has discrepances with respect to the experimental response. This may be due to the difficulty to conceive correctly the interaction between the two bodies of the building and the limitations of the expressions used to estimate the stiffness and the damping coefficients.

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