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

Response measurements of a tall building under seismic excitation

N. Rodríguez-Cuevas
Institute of Engineering, National Autonomous University of Mexico, Mexico

ABSTRACT: A tall building of Mexico City was instrumented with synchronous accelerometers, to measure three orthogonal components at 11 points distributed on the structure, in order to understand the kinematics of seismic movements, and identify possible vibration modes and soil-structure interaction. Several earthquakes have been recorded and information on time series and spectral densities has been published. In this paper, the response is compared with a mathematical model, in which the movement of the subsoil is considered as a combination of P, S,R, an L waves, and the superstructure of the building was modelled with due regard of foundation translation and rotation, in three orthogonal directions. Maximum accelerations, velocities and displacements are presented, as well as spectra of torsional movements of the building.

1. DISCUSSION AND NEW OBSERVATIONS

Mexico City was built on top of lacustrine deposits with high water content and low shear wave velocities. When earthquake movements arrive to the city, from the subduction area at the southern coast of Mexico, strong movements are generated and buildings suffer displacements and rotations, that have generated heavy damage in tall buildings. In order to improve knowledge on structural kinematics under strong motions, a 17 story building with irregular shape was instrumented with eleven accelerometers, to measure three orthogonal accelerations in each measuring point, in order to detect relative movements with respect to the foundation, as well as the combined effects of foundation, translation and rotation.
Evidence obtained from time series recorded during two earthquakes in 1990 is presented and interpreted, on basis of a mathematical model of the building and the foundation; results indicated the paramount importance of soil-structure interaction on the structural behaviour that is described in this paper.

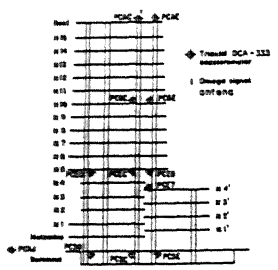
1.1 Description of the building and its foundation

The building is shown in fig 1. It has a wide basis, over a reinforced concrete box-like basement, supported by friction piles, with triangular cross section on cylindrical holes. Over the lower part of the building, there are five lateral levels used as parking lot for the tenants, at different levels, as shown on figure 1b. From the nineth floor, up to the roof, emerges a regular shaped tower for office use. Figure 1c shows a plane view of the column distribution as well as reinforced concrete shear walls, and the wall around the elevator shaft. Façades are made out of aluminum frames, supporting glass plates.

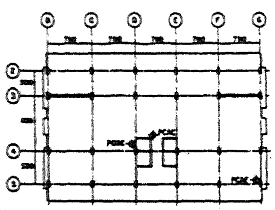
Underneath the building, the subsoil is formed by several strata of volcanic clay, typical of the lake deposits mentioned by Marsal (1962), for the lake formation under downtown Mexico, with an average density equal to 1.2 ton/cu.m, the average shear modulus of the deposit is equal to 425 ton/sq.m and shear wave velocity equal to 60 m/s. The depth of the clay deposit is equal to 35 m. The natural period of the deposit is equal to 2.4 s.

The construction was finished in 1984; on September 1985 the building was damaged and suffered partial destruction of one column at the level where the central tower begins; façades and brick walls near the stairways and elevator area were cracked. The building was retrofitted with the addition of shear walls shown on fig 1c. The façades were modified and minor details were performed.

Measurement of accelerations generated by ambient vibration at the building gave dynamic properties, due to flexure in two orthogonal directions and torsion around a vertical axis, whose first mode period was 1.79 s in flexure in two orthogonal directions, and 1.25 s in torsion. Second mode periods were 0.50 s, 0.48 s and 0.40 s respectively. All



b) Transversal view



c) Plane view of the tower

Figure 1. Characteristics of the building and structural layout

the above mentioned periods were below the natural period of the subsoil, equal to 2.4 s. Measured characteristic shapes did show the existance of common shapes in structural analysis.

1.2 Instrumentation selected for the building

The building is located at the zone of the valley where high levels of surface accelera tions have been measured by an accelerometer network already functioning at the valley. One surface station of the network in quite close (less than 500 m) and has been used as the free-field station for comparison with the instrumentation inside the building.

The free-field station has already recorded several earthquakes, whose magnitude were between 4.5 and 6.9 on Richter scale; the spectra obtained on those seisms had shown a natural period equal to 2.4 s, indicating that the properties of the subsoil have not changed after each of the recorded earthquakes.

Inside the building, digital accelerometers were attached to several columns, in order to measure time series of acceleration at four levels, to measure three orthogonal components. All the digital equipment was synchronous, in a master-slave scheme, with the same time signal, obtained from the Omega navigation system.

Accelerometers were attached to three columns at the basement; one at the center and two on columns at the corners of that level. Four accelerometers were fixed to columns at the level where the structure of the tower emerges from the lower part of the building; three in the same level and the fourth underneath the slab, in order to detect differences in displacement of the extremes of one column that was damaged in 1985.

At level 6, located at midheight of the tower, two accelerometers were installed; one at the center and the other at one corner column. Finally, two other accelerometers were attached at roof level, one at the center and the other at a corner.

Care was taken in the positioning of central accelerometers at each level, so that all of them were along the same vertical line, whereas the lateral ones were located as far as possible from the center, but along the same vertical line; further details of the instrumentation were described by Rodriguez and Quass (1990).

From the previous description, it is clear that the main objectives of the instrumentation were devoted to:

a) Definition of earthquake signal in a free-field station outside the building
b) Definition of the tridimensional response of the foundation, along three orthogonal directions, by time series that describe the displacements and rotations around three axis
c) Definition of the characteristic shapes associated to each mode of vibration
d) Detection of posible inelastic behaviour of structural elements, and change in dynamic properties, after each recorded earthquake response.

Insofar, the system has been in operation since September 1989, and several events had produced digital records on magnetic tapes; the information has been retrived after each earthquake, and processed to obtain accelerations, velocities and displacements.

Time series have been filtered and used to obtain Fast Fourier Transforms, to identify frecuency content and spectral density after each event.

Also, it has been posible to obtain relative accelerations at each level, by sustraction of time series at two parallel channels; torsional spectra has already been obtained and the results, as those shown on figure 2, are useful for interpretation of the measurements.

1.3 Generation of a mathematical model

In order to have a rational basis for measurement interpretation, a mathematical model was generated, based on structural information contained in the structural layout, and on information about material properties, mass distribution and foundation properties.

The building was modeled as a skeletal structure, formed by reinforced concrete columns and beams, whith slabs at each level and concrete shear walls. The basement was considered as a rigid box; underneath the basement, a fictitious group of columns were used to represent the foundation stiffness in flexure, torsion and two orthogonal horizontal displacements.

Fourteen plane frames, nine in North-South direction and five in East-West direction formed the model. Each frame had 24 levels, due to the existance of the fictitious floor below the basement, and the midheight levels at the parking area. The global stiffness matrix of the model was 72 x 72.

The dynamic analysis was performed by the TABS-77 program, developed by Wilson et all (1972); unidirectional movement of the model were carried out in two directions, with stiffness constants of the foundation corres ponding to different shear wave velocities of the subsoil; a plot of frecuencies of each mode due to each shear wave velocity was developed; it allowed the identification of the stiffness of the foundation, by comparison with those obtained from ambient vibration measurements. On table 1 are shown theoretical periods obtained from the model in two orthogonal directions, for built-up foundations and for the model with soil-structure interaction.

Computed values obtained from the model showed the importance of subsoil stiffness; the method developed is able to identify subsoil dynamic properties, once the period of a characteristic shape is detected. Table 1 also shows that the foundation of the building was not built up, when ambient vibration measurements were carried out. Further results indicated change of fundamental modes during earthquakes, which means that foundation stiffness is changing, due to slip of friction piles in the contact with the clay material that forms the subsoil, because measurements on the free-field station, demonstrated that the properties of the clay stratum did not change its dynamic properties, during earthquakes already recorded on the site.

In order to understand the behaviour of the clay stratum, it was modeled as a thick layer, overlying a continous medium, with elastic properties; elastic waves of P, S, R, and L type were analysed from know mathematical equations, in order to define the shape of the waves, and the rotational components of

Table 1. Periods obtained from the model for two foundation conditions (seconds)

Direction	Mode	Fixed base	Model with soil interaction
N-S	1	1.18	1.74
	2	0.28	0.65
	3	0.13	0.23
E-W	1	0.14	1.60
	2	0.30	0.30
	3	0.14	0.23

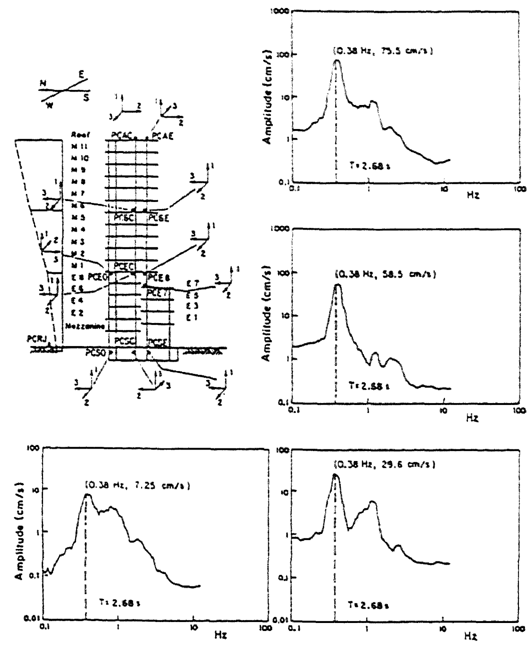


Figure 2. May 11 th earthquake spectra of motion along E-W direction

superficial particles moving with each type of wave.

Figure 3 shows the result of the analysis, and it was possible to detect that shear waves, and Love waves, produce rotations around a vertical axis, whereas P and R waves,do not produce vertical component of the rotational of the field at the surface. If the foundation of a building on top of the clay layer does not have relative movement, the building should have torsional movement due to the rotational vertical component of S and L waves. On the other way, when R and L waves appear in the upper layer, the rotational of surface particles has rotational horizontal component, which may produce rotation of the foundation of the building bearing on the upper layer of the model. The above mentioned results were used as an aid to understand the movement of the building, detected by the measuring system of digital accelerometers attached to the structure.

1.3 Earthquake records selected for analysis

On may 11th and 30 th, two seismic events were originated at the subduction zone underneath the southern coast of Mexico. Their magnitude M_{sz} were equal to 4.9 and 5.8. Both movements generated records of good quality at all measuring points and were submitted to a procedure of analysis.

Recorded time series were filtered and processed to obtain their Fast Fourier Transform; on figure 2 are shown four spectra obtained on May 11 th, on the East-West direction. It is clear that the maximum at 0.38 Hz at all accelerometers along the central vertical line, shows the existance of a natural mode of vibration, with a natural period equal to 2.68 s. This result indicates that the dynamic stiffness of the foundation had changed, because the super structure did not suffered visible damage, and subsoil properties had not changed, as shown by the spectra obtained

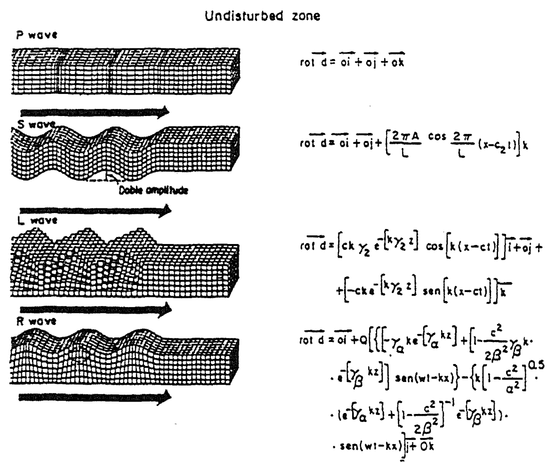


Figure 3. Wave patterns and mathematical description of rotational vector for each wave

Table 2

Maximum accelerations recorded and amplification coefficients obtained (gals)

Station	Duración s	May 11 th earthquake Maximum acceleration C_1	C_2	C_3	Orientation C_1,C_2,C_3	Duration s	May 31 st earthquake Maximum acceleration C_1	C_2	C_3	Orientation C_1,C_2,C_3
PCSC	180.3	1.20	-3.23	-2.39	V-N-E	297.4	2.15	-6.46	-5.74	V-N-E
PCSE	208.2	1.32	-2.75	-3.71	V-O-N	292.5	1.67	6.10	-7.06	V-O-N
PCSO	227.3	-1.20	-2.27	-2.99	V-O-N	292.3	2.27	-5.62	-6.70	V-O-N
PCE7	185.0	1.44	-5.74	-5.74	V-O-N	291.3	1.91	-12.92	-10.53	V-O-N
PCE7	185.5	1.91	-6.70	-5.74	V-O-N	293.0	-3.35	-13.88	-12.92	V-O-N
PCE8	192.6	1.91	-6.22	-6.22	V-O-N	291.4	-2.87	-14.83	-11.48	V-O-N
PCEO		not	recorded			302.1	3.83	13.88	16.75	V-E-S
PC6C	184.9	-3.35	8.61	-12.92	V-O-N	288.6	4.31	-18.18	-22.97	V-O-N
PC6E	186.9	1.91	-8.61	11.01	V-O-N	288.4	2.87	-21.05	19.62	V-O-N
PCAC	216.2	-2.87	-23.93	15.79	V-S-O	300.0	4.31	-39.24	33.02	V-S-O
PCAE	216.3	-2.03	-19.62	-15.31	V-S-E	151.35	-4.07	-35.41	-35.41	V-S-E
Amplification										
PCAC/PCSC		2.39	7.41	6.61			2.00	6.07	5.75	

at the free-field station. In other earthquakes already recorded, the same effect has been detected; it may be caused by slip at the interface of the friction piles with the clay stratum. When a small earthquake moved the city on September 1989, some records showed the typical beating pattern of movement of a structure close to resonance, with a natural period close to that of the clay stratum under shear wave excitation. Recorded information indicates that the building foundation has been changing its dynamic rotational stiffness. This was confirmed by the analysis of May 31st earhquake records, that showed an increased natural period of the building.

From the records obtained on both earthquakes under analysis, it was possible to define the maximum values of horizontal and vertical acceleration. Their values are shown on Table 2, as well as the amplification coefficient that relates the maximum value at the roof, with that at basement level. It is interesting to point out the amplification coefficientes in the earthquakes under analysis, were of the same order of magnitude.

1.4 Torsional responde of the superstructure

Time series information on record was processed to detect the torsional movement, by sustraction of accelerations obtained at two parallel accelerometers attached at columns at the same level of the building, in order to define the relative movement between the corresponding points. Differences at simultaneous time gave new time series and relative displacements were computed. By division of relative displacement by the ortogonal distance of accelerometers oriented in the same direction, it was possible to compute the rotations induced by torsion along the vertical central axis of twist.

Figure 5 shows the torsional responde of the building at different instants of the movement, close to the maximum acceleration recorded; it can be seen the fast changes in shape, and the existance of shapes similar

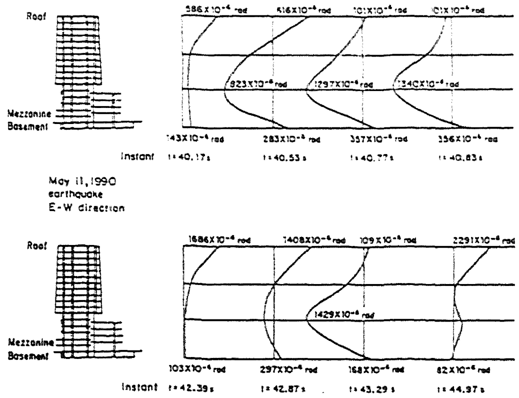


Figure 4. Torsional configurations of the building, due to May 11 th, 1990 earhquake

Table 2

Maximum relative kinematic variables obtained at the building during two recorded earthquakes

Dir	Measuring level	May 11 th, 1990 earthquake Acelera-tion cm/^{2}	Velocity cm/s	Displacem. cm	Rotation 10^{-6} rad	May 30 th, 1990 earthquake Acelera-tion cm/s^2	Velocity cm/s	Displa-cem. cm	Rotation 10^{-6} rad
	East basement	3.59	1.12	0.39	506	10.60	2.65	1.07	1390
	West basement	3.19	1.04	0.47	472	9.88	2.68	1.03	1035
E-WE	8 level	8.37	2.47	1.03	1477	23.63	7.20	2.85	1615
	6 level	5.75	1.96	0.96	1297	5.85	2.03	1.08	1459
	Roof level	13.0	3.95	1.69	2284	54.93	15.66	7.42	10027
	Amplification Roof/base	3.62	3.53	4.33	4.51	5.18	5.91	6.93	7.42
	East basement	5.03	1.56	0.48	224	7.97	2.46	0.98	458
	West basement	3.19	1.04	0.47	267	7.94	2.19	1.05	597
N-S	8 level	7.80	3.00	1.18	504	10.34	3.04	1.33	568
	6 level	6.77	2.48	1.00	476	13.46	4.33	1.76	838
	Roof level	39.15	11.94	4.76	2267	44.54	15.64	6.16	2933
	Amplification Roof/base	7.79	7.75	9.92	10.30	5.59	5.36	6.29	6.40

to second mode, although in some instants, first mode shape appears on figure 5. It should be mentioned that there is evidence that rotational movement depends of the distance between accelerometers.

Computation of Fast Fourier Transform of relative displacements gave the spectra shown on figure 6, at different levels of the building. They show similar shapes, with two peaks, one close to 0.04 Hz, and the other at a frecuency that corresponds to the natural period of the clay stratum under shear waves. As previously mentioned, only L and S waves produce vertical component of the rotational at the surface of the stratum. Therefore, the first peak may be considered to be produced by the vertical component of the rotational generated by L waves. Analytical analysis of the characteristics of Love waves shows large periods for a layer on top of a semispace; by sustitution of properties of the upper layer under the building, and assuming the depth of the stratum, a period of Love waves at the site was computed and came quite close to the one obtained from the spectra. Similar results were obtained along the North-South direction analysis of records from the same earthquake. Analysis of May 30 th earthquake records gave same type of spectra, and periods of S and L waves.

Table 3 contains data on torsional maximum response at different levels of the building on both earthquakes under analysis. It also shows the amplification coefficiente of torsional response between roof level and basement. It should be mention that the order of magnitude of those coefficients is similar to those mentioned on Table 2, for horizontal movement of the building.

2. Final comments

Earthquake records, already obtained from the instrumentation system implemented at the building under study, indicate that it is possible to obtain valuable information for engineers.

In first place, it should be mentioned that the system is operative and may produce more information from future earthquakes at the building under study.

In second place, it is important to point out that the building foundation shows evolution of its dynamic properties, that produces changes in the natural periods of the system superstructure-foundation. Careful observation of the behaviour of the building may indicate the need for remedial measures, to increase the rotational stiffness at the foundation, in order to avoid excessive tilting under future earthquakes.

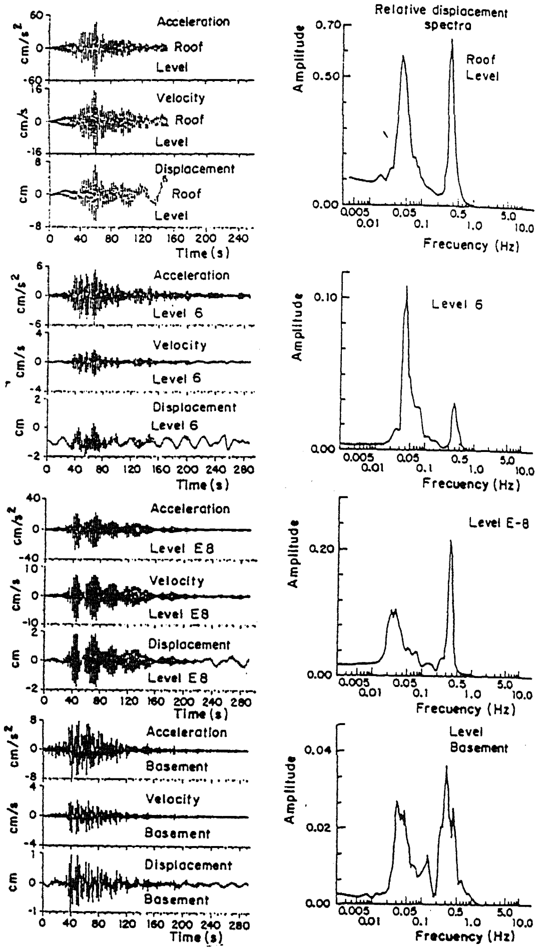


Figure 5. Torsional relative time series and relative displacement spectra obtained on May 30 th, 1990 earthquake

Thirdly, the model developed for interpretation purposes is useful to define the dynamic response of the building, and gives a clear insight on the kinematics of the movement under earthquake excitation.

The analysis of torsional response made it clear the existance of two well defined peaks at the spectra, indicative of two frecuencies, associated to Love and shear waves of the subsoil. Spectral densities at those frecuencies increses as the height from the basement increases. Vibration of the building on torsion shows continuous and fast change in the shape of the building.

Evidence previously described indicates that soil-structure-interaction has a paramount importance on the response of the soil-foundation-structure system.

Further earthquake movements at Mexico City Valley may produce new records, and the analysis of the information contained on them may give more knowledege on the dynamic response on the building.

Other buildings at downtown Mexico have been instrumented, and more information may be available in the future, to increase the knowledege of building dynamic response, with soil-structure interaction, under strong earthquakes.

3. References

Marsal, RJ y Mazari, M. 1962. El subsuelo de la ciudad de México. Facultad de Ingeniería, UNAM.

Rodriguez Cuevas N, y Quass Weppen, R. 1990 Respuesta estructural de un edificio instrumentado en la ciudad de México, durante sismos recientes. Proc. Int. Seminar on Seismic Instrumentation and use ot energy dissipators in structures. Sociedad Mexicana de Ingeniería Sísmica. 125-155

Wilson, E. L. y Dovey, H. H. 1972 Three-Dimensional Analysis of Building Systems-Tabs. EERC, Report No 72-8. University of California, Berkeley, California.