Paper No. 1422. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SEISMIC INSTRUMENTATION OF A TALL BUILDING IN MEXICO CITY

By R. MELI[1] and E. FACCIOLI[2]

[1] Institute of Engineering, Nat. Univ. of Mexico (UNAM) Apdo. 70472, México, D.F.

[2] Dept. of Structural Engineering, Technical Univ. of Milan. Pza. Leonardo da Vinci 32, Milan, 20133, Italy.

ABSTRACT

A 14-story reinforced concrete building and the underlaying soil have been instrumented with strong motion accelerographs, to study the amplification of seismic waves, the soil-structure interaction and the structural response to earthquakes of buildings founded on soft soil like that of the lake-bed area of Mexico City.

The design of the instrumentation and the results obtained during the first three years of operation (1993-1995) are also described. Six sets of records have been obtained corresponding to seismic events of moderate intensity. From the analysis of the records, important conclusions have been obtained regarding the seismic behavior of the buildings.

KEYWORDS

Seismic Instrumentation, Building Response, Ambient Vibration, Soil-Structure Interaction.

INTRODUCTION

The development in recent years of accurate, reliable and affordable instruments, as well as of sophisticated techniques of spectral analysis, has greatly enhanced the feasibility of the seismic instrumentation of buildings. Earlier instrumentation was aimed at obtaining basic indices of the response through a very limited number of instruments. Recently, more sophisticated arrays of instruments have been designed and installed to elucidate specific problems (Anderson et al, 1991, Boroschek and Mahin, 1991, Celebi, 1993 a) and b)).

Unfortunately, not a single instrumented building existed at the time of the great 1985 Mexico earthquake. Therefore, the interpretation of the building performance had to be based exclusively on damage evaluation (Rosenblueth and Meli, 1986). Since then, a great effort has been devoted to the implementation of a large instrumental network capable of recording seismic ground motions throughout the Mexico City Valley, and extremely valuable information has already been obtained from it. However, relatively limited attention has been devoted to building instrumentation. Presently, a dozen buildings are equipped with instruments to record their seismic response, and only three of them can be said to count on an instrumentation capable of providing a sufficiently detailed picture of such response. One of these buildings is the matter of this study, which derives from a joint research project of the Technical University of Milan, Italy, and the Institute of Engineering of UNAM, Mexico City.

The basic aims of the project are to improve the knowledge on local wave amplification, soil-structure interaction and especially on the structural response of multi-story buildings founded on very soft soil. For this purpose, the main task has been the instrumentation of a modern building, including its surroundings and underground.

In this paper, the characteristics of the building and of the instrumentation are described, and the studies conducted to determine the dynamic properties of the subsoil and of the building are summarized. The records obtained in the first three years of operation of the instrumentation are presented with a general interpretation, along with some conclusions about the seismic behavior of the building.

Additional studies performed with the results of the instrumentation are being presented in other papers of this Conference. The studies on site response and on soil-structure interaction can be found in the paper by Paolucci et. al.; system identification analyses of the experimental data and prediction response for high intensity motion in the paper of Gonzalez and the analyses of theoretical models of the structure in that of Muria-Vila and Gonzalez.

DESCRIPTION OF THE BUILDING AND DETERMINATION OF ITS STRUCTURAL PROPERTIES

Description of the building

The JAL building is a 14-story reinforced concrete structure erected in the seventies and occupied by offices, except for the first three stories devoted to parking. Originally, the structure consisted of a waffle flat-plate (450 mm thick) on relatively slender rectangular columns, with a small core of concrete shear walls around the shaft for staircases and elevator, and with masonry infill walls in the end frames of the longitudinal direction. After the 1985 earthquake, additional concrete walls were placed in the longitudinal direction and the section of the columns was significantly increased by a procedure known as jacketing. Figs 1 and 2 show a schematic view of the structure.

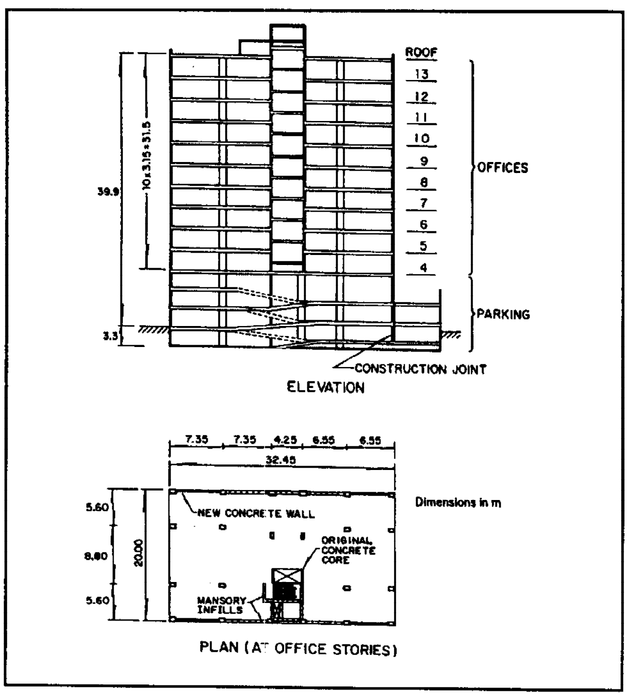

Fig.1 Schematic view of the instrumented building

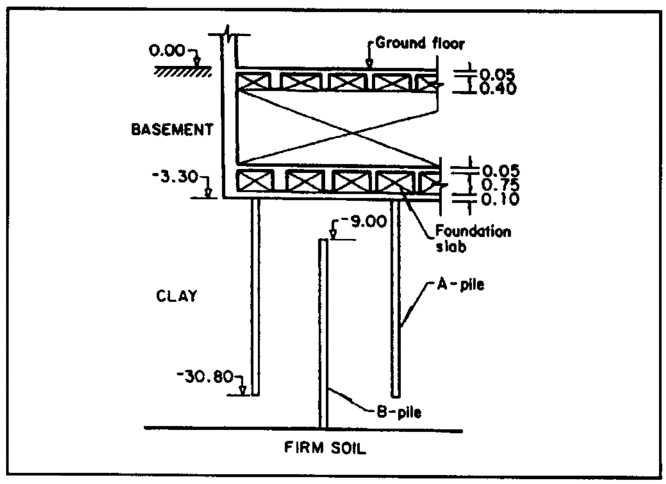

Fig.2 Vertical cross section of the building foundation

The detailing of the reinforcement does not comply with present requirements for ductile structures, especially regarding the transverse reinforcement in columns and in slab-column joints. The foundation consists of a concrete slab on friction piles, driven in a rather peculiar solution, called interweaving piles. As shown in Fig 2, the so called A-piles are fixed to the foundation slab and driven into the clay soil without reaching the firm layers. B-piles are driven down to the firm layer, but are separated from the foundation. The weight of the building is assumed to be supported by the lateral friction of the piles, and partially transferred from the A-piles to the B-piles, thus avoiding a foundation failure while allowing the building to sink following the regional settlement of the ground. The response of this kind of foundation to seismic forces is not well known. Several buildings on friction piles suffered severe rocking motion and showed significant out-of -plumb after the 1985 earthquake.

The JAL building suffered moderate structural damage in the 1985 earthquake, consisting of shear cracking of columns and masonry infill walls, especially above the seventh story. Widespread cracking of the ribs of the waffle slab was also evident. No appreciable settlement of the foundation was observed. The structure was then strengthened as previously described, without any modification to the foundation.

Field Studies

Geotechnical investigations were performed directly under the building and in a parking lot in front of it, where a free-field instrument was to be placed. These investigations consisted of cone penetration testing (CPT), plus selective sampling and seismic cone testing (SCT) at the free-field site. Under the building only the CPT was executed.

The soil profile at the building site (Fig 3) is typical of the lake-bed area of Mexico City. In general terms, beneath a surficial crust of about 5 m, the upper clay deposits extend to a depth of 29.5 m, followed by a 3 m thick intermediate firm layer. The lower clay layer extends from 32.5 to 38.5 m depth, followed by the so-called deep firm deposits. As shown in Fig 3, the shear wave velocity increases with the depth of the clay layers. An average velocity of 68 m/s was used in the calculations.

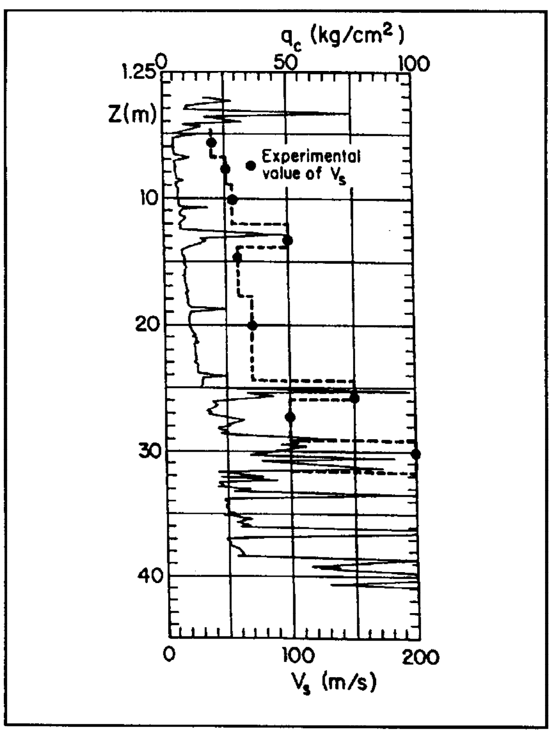

Fig.3 Shear wave velocity (Vs) profile and cone penetration resistance (qc) at the building site

The dimensions of structural members were measured and the position of the reinforcement was checked throughout the structure. No major discrepancies with values specified in the structural drawings were found. In the shear walls added to retrofit the structure, it was ascertained that the connection to the original structure was properly performed only through the upper slab, not so along the bottom slab and the sides of the wall.

Properties of concrete were determined by coring and by indirect methods (rebound hammer and ultrasonic tests). Quality was rather uniform throughout the structure.

Ambient vibration tests

To determine the main dynamic properties of the building, the vibrations induced by traffic and wind were measured. A set of eight one-directional accelerometers was used in eleven different setups, each selected to identify a particular vibrational mode or characteristics of the vibration of the structure and its interaction with the soil.

From the spectral analysis, natural frequencies were derived, as shown in Table 1. A clearly dominant frequency of the soil deposits could be identified as 0.5 Hz. Several rounds of ambient vibration measurements were performed, some before and immediately after the completion of the instrumentation and other after each significant earthquake.

TABLE 1. EXPERIMENTAL VIBRATIONS FREQUENCIES FOR THE FIRST MODE

Event	Max acc gals			Natural Frequencies (Hz)		
	Ground	Roof	Max drifts ($x\ 10^{-3}$)	T	L	R
AV-1	-	< 0.1	-	0.44	0.73	0.83
93-3	4.5	11	0.46	0.37	0.65	0.60
93-4	10.7	28	0.94	0.35	0.61	0.56
93-12	13.2	56	1.42	0.35	0.57	0.53
AV-2	-	< 0.1	-	0.44	0.70	0.68
94-1	6.6	19	0.45	0.37	0.55	0.55
94-3	17.1	124	3.45	0.30	0.47	0.47
AV-3	-	< 0.1	-	0.44	0.65	0.67
95-1	37.5	130	4.71	0.28	0.45	0.43
AV-4	-	< 0.1	-	0.43	0.67	0.65

AV-1, AV-2, AV-3, AV-4 Subsequent Ambient Vibration Test
93-3, 93-4, 93-12, 94-1, 94-2, 95-1 Earthquake Records

From the examination of Table 1 it can be appreciated that the natural frequency in the transverse direction (0.44 Hz) is very low for a building of this height, showing that the structure is extremely flexible in this direction. Fundamental frequencies for the longitudinal direction (0.73 Hz) and for torsion (0.83 Hz) are greater but not too far from the dominant frequency of the soil (0.5 Hz). Therefore, under small amplitude motions a near resonance condition is to be expected for the transverse direction, whereas for a greater shaking capable of producing non linear response and reduction in the vibration frequencies, resonance problems can arise for the longitudinal direction and for torsion. Moreover, the similarity between the vibration frequencies for the latter vibration modes will give rise to coupling and significant amplification of motions.

SEISMIC INSTRUMENTATION

Purpose

The instrumentation was designed to provide: a detailed record of the building vibration during earthquakes, a precise appraisal of the soil-structure interaction, and a picture of the wave amplification from the deeper layers to the surface.

For that purpose, the set of 14 instruments shown in Fig 4 was devised, where the instrument at 45 m depth (W2) penetrates 5 m in the deep firm strata; that at 20 m depth (W1) is near the level of the pile tips, and the free-field instrument (G) is about 50 m away from the building. All instruments are tridirectional solid state, digital accelerographs (Terratech DCA-333R), interconnected in a master-slave configuration to allow for a simultaneous trigger when the threshold of the master instruments is reached.

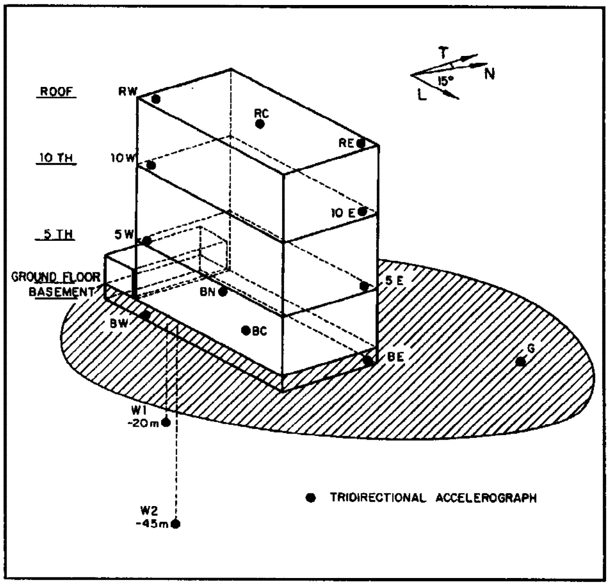

Fig. 4 Overview of the building instrumentation

Records obtained

During the period from 1993 to 1995 a large number of records have been obtained, the most significant of them are 6 sets corresponding to moderate earthquakes form the Pacific subduction zone, which induced in the building accelerations not exceeding 130 gals and maximum intensity drifts up to 0.47 percent, as reported in Table 1.

GENERAL INTERPRETATION OF THE RECORDS OF MAY 14 AND OCTOBER 24, 1993

An overview of the most significant records of the 93-3 and 93-11 earthquakes is given by Fig 5, which compares the horizontal accelerations measured at different levels, from the deep firm soil strata to the top of the building, for the transverse direction of the building plan. The two sets of records show similar trends. The frequency of 0.5 Hz dominates the motion at the base and at different heights of the building, indicating that the building is subjected to a forced vibration whose frequency is that of the soil deposits.

The underground motion in the deep layers W1 and W2 is greatly amplified at the ground surface (G), where the maximum recorded acceleration is, as an average for the three events, 3.2 times that at the deep firm deposits. The maximum roof accelerations are amplified three times with respect to the ground level, as an average for the three sets of records. Note that the duration of the 93-11 event is nearly twice that of the previous two events, due to the more pronounced "coda" effects in the acceleration time histories.

The contribution to the building vibration from different sources of deformation is illustrated in Fig 6, for the 93-3 and 93-11 events. The time history of the total displacements at the center of the roof level in the transverse direction is shown, along with the displacements due to in-plane rotation (torsion) and to rocking and translation at the base.

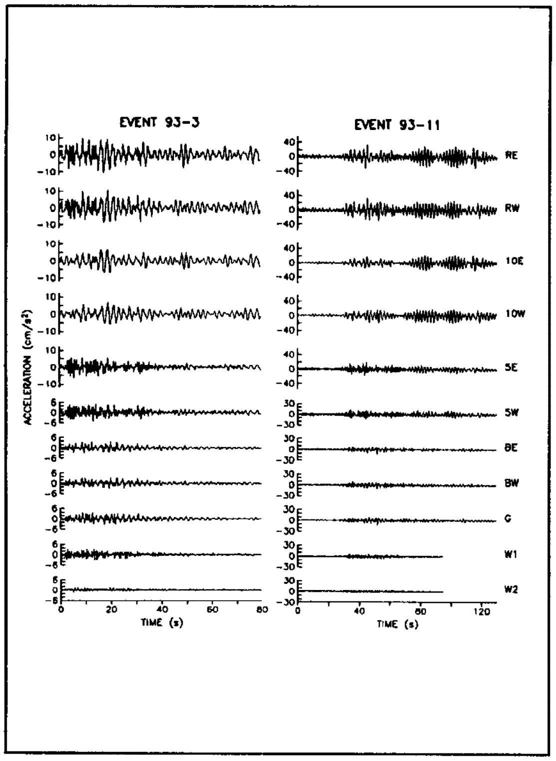

Fig. 5 Aceleration history in the transverse heights for two seismic events

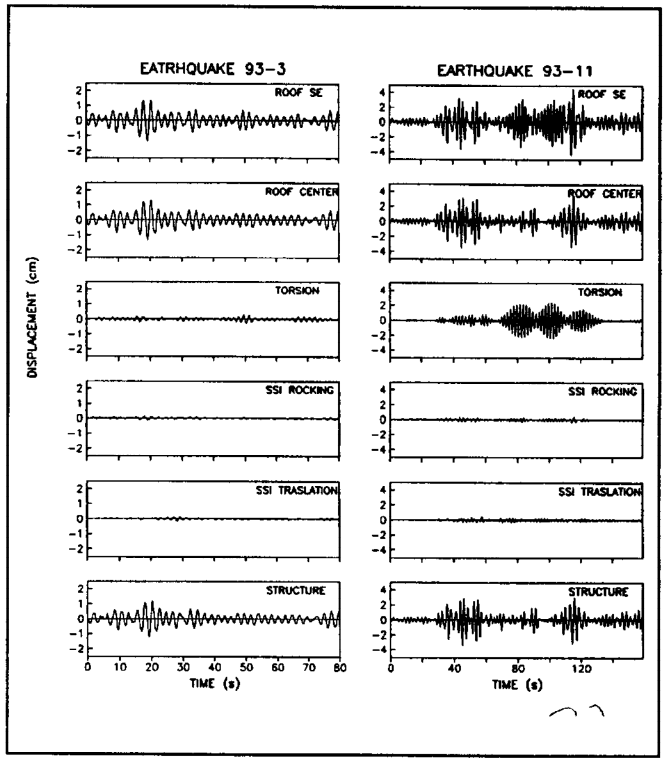

Fig. 6 Time histories of transverse direction at different displacements at roof level, with contributions of different sources of motion

As it can be appreciated from Fig 6, the deformation due to the lack of fixity of the base is not significant for both events. The torsional vibration is relatively small in the first event, but becomes very appreciable in the second one. The difference must be due to the characteristics of the motion imposed at the base of the building. Records of the 93-11 event show beatings with frequencies in the range between 0.03 and 0.05 Hz. These beatings are attributed to the similarity of the prevailing period of thesoil and the natural periods of the structure for torsional and longitudinal vibrations. The samephenomenon has been detected in other instrumented buildings (Boroschek and Mahin, 1991).

Fig 7 shows the transfer functions between the motions at the roof, both transverse and longitudinal, and the free-field motion, for the three events. The frequencies of the first modes of vibration in both directions are clearly identified. The transfer functions and phases between the motions at a corner and at the center of the roof are shown in the same figure allowing the identification of the fundamental torsional mode. The frequencies of vibration derived from the seismic records, shown in Table 1, are significantly smaller than those obtained from the ambient vibration tests; they also tend to decrease for increasing intensities of the motion. The difference is greater for the torsional mode of vibration.

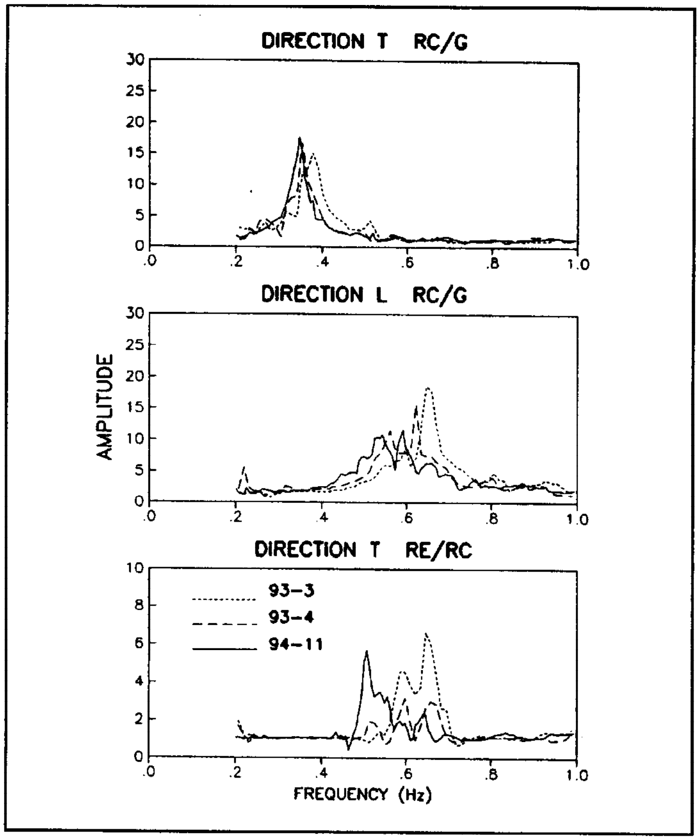

Fig. 7 Transfer functions between the motion at the roof center and at free-fiel (RC/G), and between the corner at the center of roof (RE/RC)

As it can be appreciated from Table 1, the natural frequencies obtained from the second round of ambient vibration tests are again greater than those derived from the seismic records and are similar to those obtained before the three earthquakes. Therefore, the shortening of the vibration frequencies can be attributed to early non-linear behavior of the building more than to permanent structural damage. The level of stresses induced during the ambient vibration tests are much smaller than those generated by earthquakes, and therefore, correspond to greater stiffness of the structure. Nevertheless, for the torsional mode the final frequencies are significantly smaller than the initial ones, indicating that the somepermanent reduction in stiffness had occurred. As explained later this reduction in stiffness is attributed to some decrease in the contribution of the masonry infills.

Damping ratios for the fundamental modes of vibrations were derived from the transfer functions between the roof and free-field. Ratios between 2 and 6% of the critical damping were obtained.

FINAL REMARKS

The study of the building is expected to continue for several years enabling us to gather a more complete set of records corresponding to a wider range of earthquake intensities, and to obtain a more complete picture of the evolution of the dynamic properties of the building. At this stage, some conclusions can be advanced.

The dynamic response of the structure showed to be very sensitive to the amplitude of the imposed ground motion. Early non-linear behavior produced continuous reduction of the lateral stiffness with increasing level of stresses.

The rocking and translation of the base of the building founded on very soft clay have a moderate effect on the overall displacements. They reduce the fundamental frequencies in the transverse and longitudinal directions by 10% and 25%.

The building under study is extremely flexible, especially in the transverse direction. Furthermore the fundamental frequency in such direction is close to the dominant frequency of soil, giving rise to great amplifications of the imposed motions. Also, the fundamental frequency in the longitudinal direction is close to that in torsional vibration, producing coupling and amplifications of the two modes of vibration.

ACKNOWLEDGEMENTS

The research project on which this paper is based has been sponsored by the European Commission, under contract CI1-0674-I, and the National Council for Research and Development (CONACYT, Mexico). The support of the Department of Public Works of the Mexico City Federal District has also been very valuable.

Mario Ordaz and Ricardo Gonzalez-Alcorta have contributed to the interpretation of the records, David Muria and Roberto Paolucci, together with the authors of this paper, were responsible for the research project.

REFERENCES

Anderson, J.C., E. Miranda and V. Bertero (1991). Evaluation of the seismic performance of a thirty-story RC buildings. *Report No. UCG/eerc-91/16*, University of California at Berkeley.

Boroschek, R. and S.A. Mahin (1991). Seismic response of a lightly-damped torsionally-coupled building, *Report No. UCB/EERC-91/18*, University of California at Berkeley.

Celebi, M. (1993). Seismic responses of two adjacent buildings. I: data and analyses, *J. of Struct. Engrg. ASCE*, 119(8), 2461-2476.

Celebi, M. (1993 b). Seismic responses of two adjacent buildings. II: Interaction. *J. of Structural Engineering, ASCE*, 119(8), 2477-2492.

Muriá-Vila, D. and R. González A. (1996), Seismic Response of a Tall Building in Mexico City, *Proc. 11WCEE*, Acapulco, Mexico.

Paolucci, R., E. Faccioli and M. Vanini (1996), Studies of Site Response and Soil-Structure Interaction Effects in a Tall Building, *Proc. 11WCEE*, Acapulco, Mexico.

Rosenblueth, E. and Meli R. (1986). The 1985 earthquake; causes and effects in Mexico City. *Concrete International*, ACI, Vol 8, n. 5, 23-34.