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USE OF RECORDED SEISMIC EVENTS OBTAINED AT A BUILDING, FOR ESTIMATION OF ITS RESPONSE UNDER EARTHQUAKES FROM DIFFERENT EPICENTERS

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SUMMARY

During four years, two instrumented buildings at the transition zone of Mexico City recorded 19 seismic events, with magnitudes between 5.0 and 7.5, coming from different epicenters along the subduction zone at the Southern Coast of Mexico. Recorded data were used to develop a statistical model in which the magnitude, azimuth and distance from the epicenter to the buildings were used as main variables, to estimate the variance and maximum acceleration at the top and the base of the buildings, as well as its directions and maximum acceleration. With this information and a three dimensional model in which soil structure interaction was considered to represent the structural response of the buildings, it was possible to estimate the effect of earthquakes on the buildings, with epicenters distributed along the subduction fault at the Pacific Coast of Mexico. Information is presented on the statistical model developed, its reliability, and its possible use to generate motions and mechanical elements on different parts of the buildings, under the action of strong earthquakes.

FOREWORD

On a previous paper, (ref 1), presented at the 12th World Conference on Earthquake Engineering, mention was made of two instrumented buildings, Fig.1, located at the transition zone between soft clayey soil, and the hills surrounding Mexico City; instruments were located to obtain digital records of motions generated by strong earthquakes, whose epicenters were located at the Southern coast of Mexico. Structural analyses were developed to reproduce their motion, with due consideration to soil-structure interaction. Identification of dynamic variables of the structure, such as modal shapes, frequencies, and damping, during forced excitation was achieved, as well as the accelerations generated at different parts of the buildings, when their representative model was excited by recorded signals. The accelerometric network operated since 1997 up to 2001, and captured acceleration time series at the measuring stations, from three orthogonal sensors, during 19 earthquakes.

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In this paper, an evaluation of the retrieved information was done, and a statistical model was developed, to reproduce the maximum accelerations recorded at the buildings, and for the evaluation of virtual seismic events, originated at different epicenters at the southern coast of Mexico.

a) Instrumented buildings at Mexico City

b) Building A is shown at the right side

Fig 1.General view of the buildings

OBJETIVES AND ATTAINED GOALS

The search for information had the following objectives:

- Identification of the transmission pattern of seismic waves, from the focal zone, to the instrumented buildings
- Correlation between the relative position of the focal zone and the building and the direction of the incoming seismic waves
- Development of an empirical statistical relation between earthquake characteristics and maximum accelerations recorded at the measuring stations
- Possible change in structural properties of the buildings, generated by earthquakes, as a measure of structural damage

All the above mentioned objectives were achieved; an empirical model for maximum accelerations on the buildings was finally developed.

SUBSOIL DESCRIPTION

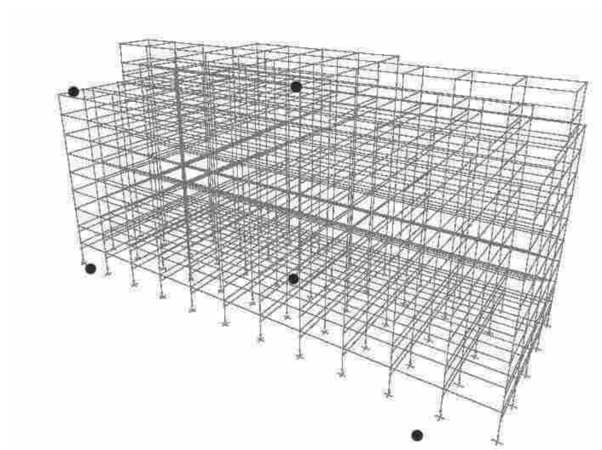
Geotechnical exploration on the site, gave a subsoil profile with several strata, under the building basement, with a superficial stratum under which, well consolidated clay and silt strata extended down to 21 m depth, intermixed with shallow sand and volcanic material. Under this layer, a rather compact alluvial stratum was found, with sand, silt and andesitic gravel, slightly cemented; down to 30 m, more clay and alluvial materials were found. Under 35 m depth, a compact stratum of fine sand, clayey silts and andesitic gravels, well cemented, were found.

Dynamic estimates of the shear deformation modulus G, indicated a value equal to 6400 tons/sq.m, as representative of the site response, to seismic excitation.

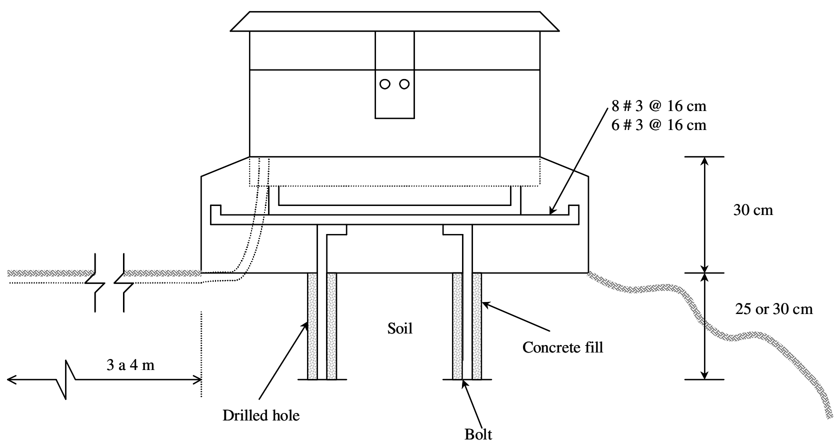
ACCELEROMETER NETWORK DESCRIPTION

Four measuring stations, equipped with EDNA accelerographs, were installed at each building, interconnected with a master sensor at the roof; the rest, formed a master slave system. Also a signal sent by a geodesic satellite was captured, to set time record at each station. Two station were located at the roof level, and two others were positioned at the same vertical line, from those on the roof, at the basement of the buildings. The horizontal sensors had N25°E orientation on the longitudinal direction, and N65°W on the transverse direction of the buildings; the vertical sensor was orthogonal to them.

A free field measuring station was located nearby, with its sensors parallel to those in the instrumented buildings. Fig 2 shows the relative position of the measuring stations in one building, as well as the free field station. Each accelerometer was calibrated for a threshold value, so their activation could be set in operation, when earthquake magnitude exceeded M_L =4.5.



a) Relative positions of recording stations at building A

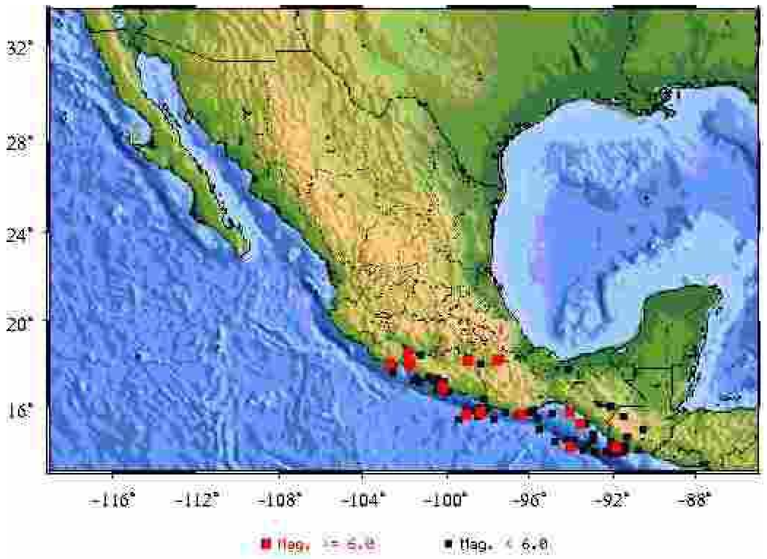


b) Typical free field recording station

Fig. 2 Schematic view of recording stations of the accelerometric network

INFORMATION COLLECTED BETWEEN 1997 AND 2001

Seismic activity at Mexico City Valley is highly dependant on plate motion at the south coast subduction zone, where the majority of epicenter areas are located, as shown in Fig. 3a. Earthquakes whose epicenters lay on that area, in the lapse 1990 to 2000, appear at Fig. 3b. Their number per year, varied from 622, up to 1097. Many earthquakes detected on that lapse, had magnitudes lower than M_L= 6; only less than 0.5 percent of them had magnitudes with M_L bigger than 6.



a) Epicenter location of earthquakes recorded by the National Seismologic Service during the observation period

Year	Annual total events	Earthquake magnitude						
		<3	3	4	5	6	7	8
1990	792	13	246	509	23	1	0	0
1991	732	6	184	510	30	2	0	0
1992	613	5	183	398	27	0	0	0
1993	917	48	275	548	40	5	1	0
1994	622	20	192	383	24	3	0	0
1995	676	16	188	438	26	6	2	0
1996	790	9	203	543	32	3	0	0
1997	754	42	262	420	26	2	2	0
1998	707	8	270	403	23	3	0	0
1999	1097	13	540	527	11	4	2	0
2000	1052	37	463	531	18	2	1	0

b) Earthquake activity and their magnitude from 1990 up to 2000, by the Mexican National Seismological Service, at the southern coast of Mexico

Fig. 3 Origin and number of earthquakes generated at the subduction area

Acceleration time series originated by earthquake motions were recorded by the accelerometer network installed at the instrumented buildings, during the four year operation period; 19 seismic events, whose magnitudes were in the 4.8-7.5 range, were captured. Most of them had epicenters located at the south coast subduction zone. Fig. 4 shows the epicenter position of those earthquakes. The National Seismological System has detected the relative position of the focal area of most of the earthquakes generated at the subduction zone (ref. 2); Fig. 5 shows their distribution. Their focal zones lay in a 10-250 Km depth range; at the western side of the coast, rather shallow focal zones are found; moving to the East, their depth increases, and at the eastern part, rather deep focal zones are found. This information was use, in order to define the eventual position of focal zones for hypothetical earthquakes, along the subduction area, for the estimation of their effects, on the instrumented buildings.

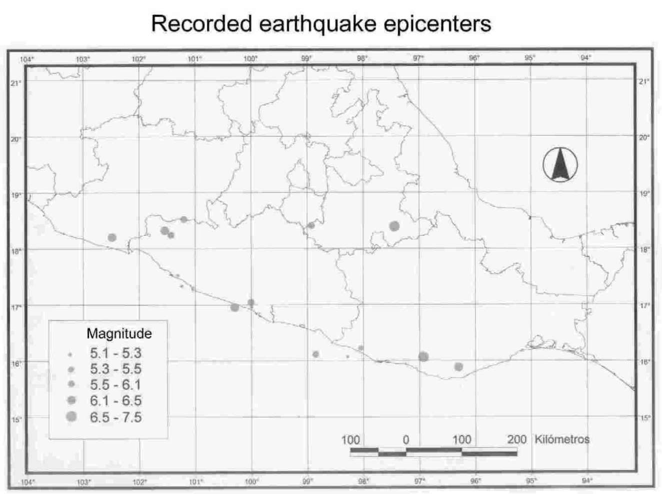


Fig. 4 Epicentral relative position of recorded earthquakes by the accelerometric network at the instrumented building

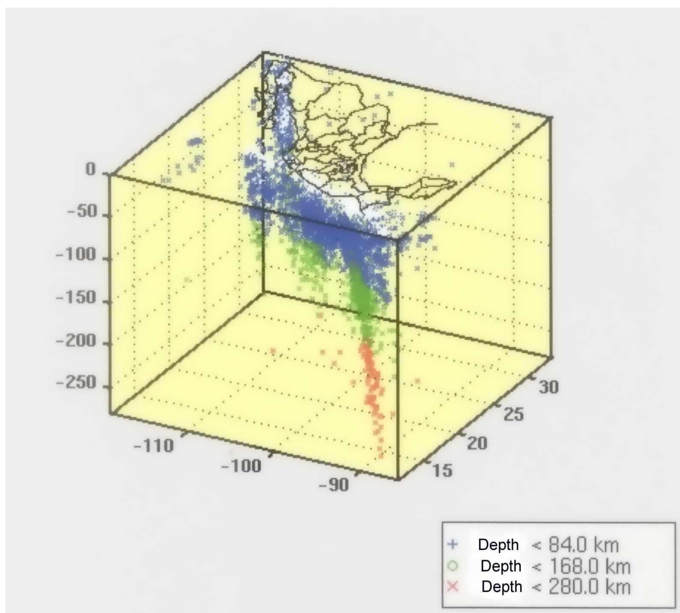


Fig. 5 Focus relative position of seismic events generated at the subduction zone at the south of Mexico

During the observation period, 69 time series representing acceleration records were captured; each recording channel was identified, as well as its duration, initial and final time, and the acceleration magnitude variation. Data analyses indicated that on September 30th, 1999, a strong earthquake, with M_s = 7.5, arrived at the buildings, with a maximum acceleration equal to 59.79 Gal, in the N65°W direction;60.02 Gal in N25°W direction; in vertical direction, the acceleration was 6.68 Gal, at the sensors located at the center of the roof level. At the free field station, the corresponding values were 17.43 Gal; 24.18 Gal and 9.37, respectively.

NUMERICAL PROCESSING OF DIGITAL RECORDS

Recorded time series were used as input of Degtra program (ref 3), searching for the following results:

- Arias' intensity (between 45 and 1920 at free field station)
- Arias' duration (average value 36.2 s, with 33.8 percent as variation coefficient)
- Maximum and minimum acceleration at each record
- Elapsed time for maximum acceleration (90 s for the strongest motion)
- Variance of each time series (average at the roof, 48.3 Gal^2 with 195% coefficient of variation. At free field, 13.68 Gal^2)
- Standard deviation (average 4.76 Gals, with 115 percent as coefficient of variation)
- Ratio between maximum acceleration an standard deviation (average 3.43, with 20.36 coefficient of variation)

Additionally, Fourier's spectrum for each record was computed, as well as transfer function and coherence, between signals obtained at parallel sensors. This information showed that the dynamical properties of the buildings did not suffer any modification during the observation period. This result is significant for the structural behavior of the buildings, pointing out that the stiffness matrix did not deteriorate, after earthquake motions. Therefore, the original three-dimensional model developed, may reproduce the behavior of the building structure, after each seismic motion.

STATISTICAL MODEL

The procedure recommended for system identification of a representative model was followed (ref 4), in order to develop a mathematical model able to reproduce measured results. Fig. 6 shows the procedure followed to develop the model, where three principal actions were followed:

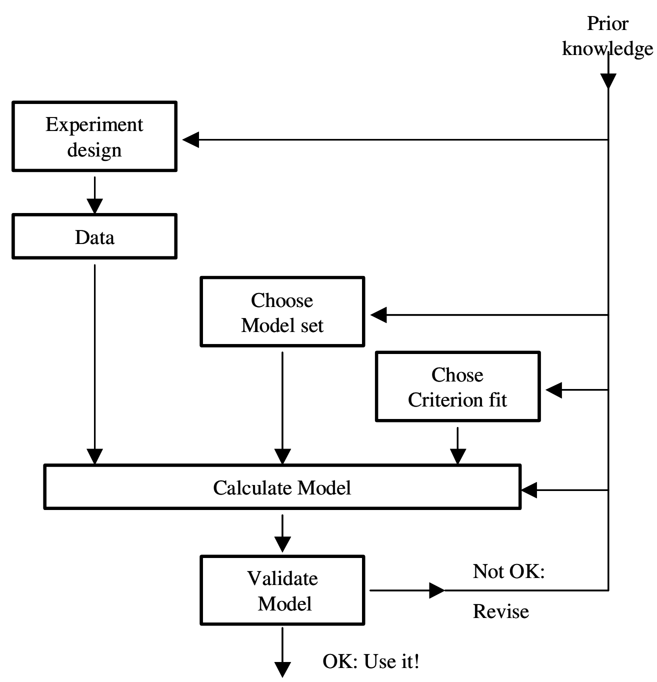


Fig. 6 The system identification loop

a) Use of the recorded information, as input for a controlled experiment. The input data were selected from the recorded information, at each measuring channel.

b) Selection of a basic model. Previous experience (ref. 5) developed an empirical mathematic model to represent motion of the terrain surface, based on data recorded a 29 recording stations at different sites of Mexico City Valley, after 9 earthquakes. The empirical expression was selected as initial model, whose empirical constants were modified, to represent motions generated at the site where the buildings were built

c) Selection of the best model. Based on the retrieved data, the initial model was validated, by minimum error criteria, from comparison of the computed values, with those obtained from measurements

Logical base for the method is shown on Fig. 7. When rupture appears at the focal area, an earthquake is generated, and seismic waves appear, represented by time series,{i(t)},radiating in three orthogonal directions from the rupture area. Waves move along geological formations, and reach a surface point where the free field station is located. At that point, time series are recorded, as {f(t)}. This waves are filtered though soil-structure interaction, and generate {b(t)} time series at the basement of the structure.

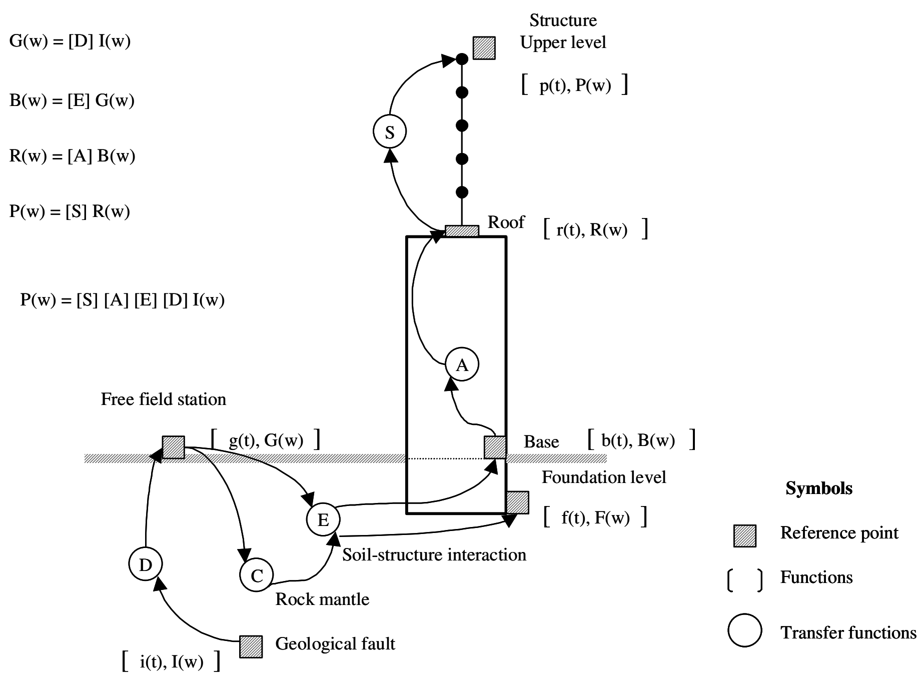


Fig. 7 Schematic representation of earthquake transmission motion

These motions produce motions along the structure height, whose flexibility modified, and amplify the motion; at an intermediate point, {r(t)} represent the acceleration time series. Finally, at the top of the building {p(t)} represent amplified time series induced by the earthquake.

Mathematically, each of the time series can be transformed, through Laplace transform, or Fast Fourier transform, to obtain spectral density functions on frequency domain, represented by {I(w)}, {F(w)}, {G(w)}, {B(w)},{R(w)}, and {P(w)} respectively.

As previously mentioned, the structural behavior of the buildings was linear; therefore the transformed functions may be related through transfer functions on the frequency domain, represented by [D],[E], [A] and [S] at Fig. 7, dependant on material properties through which the seismic waves travel.

For stable motions, the maximum response, described by p(t), may be related to the motion generated at the focal zone, through the relation on the frequency domain described by:

$$P(w) = [S] \cdot [A] \cdot [E] \cdot [D] \cdot I(w) \qquad (1)$$

Therefore, it becomes evident that when free field records exist,

$$G(w) = [D] \cdot I(w) \qquad (2)$$

being [D] a transfer function that depends on the dynamic properties of the geological formations through which the seismic waves travel, from the rupture area, to the free field recording station. Similarly, when the free field motion is known, through transfer functions, is possible to reproduce motion at intermediate points and at the top of the buildings.

The previous logical sequence was developed to understand motions created by an earthquake; it clearly indicates that the acceleration spectral density to be obtained at each measuring station is highly dependant on:

a) Focal area and tensor moment associated to the earthquake

b) Trajectory pattern followed by waves emerging from the source, until they reach the sensor location at each measuring station

c) Relative direction of the waves, with respect to the vector drawn from the sensor, to the focal area

d) Sensor properties at the measuring station

Because all sensors came from the same factory, the sensor type has the same effect on all records; therefore, the differences on the recorded information should be attributed to:

a) Characteristics of the earthquake at the focal zone

b) Geological and geotechnical properties along seismic waves path

c) Wave direction between the source and the instrumented buildings

d) Building dynamic properties at the measuring station

From previous analyses of recorded seismic time series captured at Mexico City Valley, (ref. 5), evidence was obtained that the standard deviation of each record, as well as its variance and maximum acceleration value, are related to the earthquake properties, by the following expressions:

a) Standard deviation $$DE = C_4 \left[e^{\left\{ \frac{Ms}{C_1} - \frac{\Theta R}{C_3} \right\}} \right] (N)^{C_2} \quad (3)$$

b) Record variance $$\sigma^2 = (DE)^2 \quad (4)$$

c) Maximum acceleration $$A_{\max} = (FA)(DE) \quad (5)$$

d) Amplification factor $$(FA) = (A_1 M_s + A_0) \quad (6)$$

being:

C_1, C_2, C_3, C_4	Constants obtained from statistical adjustment
M_s	Earthquake surface waves magnitude
Θ	Position vector azimuth, degree/180°
R	Focal area distance from the instrumented building, Km
A_0 , A_1	Adjusted constants from measurements
N	Identification station number

For model development, each record variance was considered as a vector, whose magnitude was equal to the computed variance, and its direction corresponded to the sensor direction at each measuring station. The orthogonal vectors at each measuring point produced a resultant vector, whose azimuth was compared to the azimuth of the position vector connecting the instrumented building, and the earthquake epicenter, in order to define a relationship between them.

SEISMIC WAVES DIRECTION IDENTIFICATION

On previous reports, (ref. 6, 7) mention is made of the relationship between the azimuth of the position vector connecting a measuring station, and the epicenter position, when waves generated by an earthquake, arrive to a measuring station.

In order to prove this relation, from recorded time series at a measuring station, obtained from the horizontal orthogonal channels, computations were carried out to obtain the variance of each record, and the total horizontal variance was obtained, by adding the variance computed from each horizontal channel; it was considered as the magnitude of vector, whose components were assigned the orientation of the corresponding direction of the recording sensor.

Variance vector direction was compared with that of the position vector, defined by the geographic point of the measuring station as origin, and its extreme located at the epicenter zone, of the earthquake source. Azimuth of both vector were compared, and their difference, divided by the azimuth of the position vector, was considered a measure of relative error.

Computations were carried out looking for errors obtained for the earthquakes recorded at the free field station, for all the events that generated time series at that point. Average error value was equal to eleven percent; similar computations were carried out for the recoded time series atop the instrumented building, and the average error value was in the same order. Therefore, the evidence allowed acceptance of the relation between incoming waves direction, and that of the position vector.

That result was used for simulation computations, when earthquake epicenters were located along the southern coast, and incoming virtual waves, with known deviation, produced time series at each recording channel, whose deviation was estimated by decomposition along direction of each horizontal channel.

STATISTICAL MODEL VALIDATION

In order to test the reliability of the model already described, computations were carried out to define the constants involved in the model, by comparison with those obtained from measurements, using an minimum error criterion, as basis for evaluation and adjustment of constants.

The following expression was obtained to compute standard deviation at free field station, of all acceleration time series, generated by an earthquake with known M_s magnitude, and epicenter position:

$$(DE) = 0.1748\left[e^{(0.165908Ms - 0.00313850R)}\right] \tag{7}$$

To compute the amplification factor (FA), the following expression was obtained:

$$(FA) = (28.062564M_s - 84.236042) \tag{8}$$

The maximum acceleration expected in a horizontal plane at the free field station, can be computed by the following definition:

$$A_{\max} = (4.905336M_s - 16.47246)\left[e^{(0.165908M_s - 0.00313850R)}\right] \tag{9}$$

The acceleration resulting from expression 9, can be projected along the direction of each sensor at the field station, in order to estimate the maximum acceleration at that channel, when the earthquake waves arrive to the station.

In order to validate the above expressions, for every recorded earthquake at the instrumented building, computations were carried out to obtain the values corresponding to each earthquake; looking for the computed accelerations on each channel, as well as the quotient resulting from the ratio between the estimated maximum acceleration at each sensor of the free field station, and that measured at that channel. This quotient was used to estimate the error level resulting from the comparison. Computations indicated that the average value of the quotients selected to estimate the relative error, was equal to 0.9892, with a coefficient of variation equal to 54 percent.

To complete the model, analyses were carried out in order to relate maximum acceleration recorded at the roof sensors located at the building, with those recorded at free field station. For that purpose, a Translation Factor (FT) was computed, defined as the existing ratio between the maximum acceleration value at roof level recorded at sensors at the roof, and the corresponding sensors at free field station. Results indicated that the translation factor FT, depends on the earthquake magnitude M_s, but statistical analysis of its value gave an average value equal to 2.3464, and a standard deviation, equal to 0.8644

Therefore, the following expression may be used in order to estimate maximum horizontal acceleration at roof level, $(A_r)_{max}$, once the maximum horizontal acceleration at the free field station, (A_{max}), is estimated, multiplying it by the translation factor (FT).

$$(A_r)_{\max} = (FT)(A_{\max}) \tag{10}$$

Once the maximum acceleration at roof level is known, its components can be estimated, assuming that the seismic event waves have the same direction as the position vector of the earthquake epicenter, referred to the building geographic position.

EFFECT OF SIMULATED EARTHQUAKES ON THE BUILDING

For evaluation purposes, the statistical model developed was used to evaluate the expected acceleration level, at free field sensors, and roof level channels, when virtual seismic events appear, whose epicenter zones could be located at hypothetical points along the Mexico southern coast.

Virtual epicenters were located at the points of intersection of meridians and the south coast, separated one degree in geographical longitude, from the point with 95°W longitude, up to the point located at longitude 104°W. At every epicenter, an earthquake with magnitude M_s = 8.1 was considered, with a focal depth dependant on its relative position; focal depth varied from 80 Km at the first eastern epicenter, up to 17 Km to the one located at 104°W, with linear variation along the coast.

Once the epicenter position was defined, distance R from the focal zone to the building was computed, as well as the corresponding azimuth of the position vector, Θ ; information for all the virtual earthquakes is shown at Table 1.

Table 1 Virtual epicenters position for simulation

Point	Latitude	Longitude	Depth	R	Theta	Ms	(FA)	(DE)	A_{max}
A	16.14	95	80	591.04	127.83	8.1	6.33	8.8314	55.8966
B	15.81	96	73	538.92	138.88	8.1	6.33	8.9410	56.5904
C	15.81	97	66	473.05	149.18	8.1	6.33	9.6331	60.9705
D	16.14	98	59	390.04	160.47	8.1	6.33	11.0711	70.0724
E	16.57	99	52	322.52	176.8	8.1	6.33	12.1999	77.2170
F	16.4	100	45	299.62	200.41	8.1	6.33	11.5730	73.2486
G	17.24	101	38	320.11	224.48	8.1	6.33	9.4188	59.6141
H	17.98	102	31	355.69	249.95	8.1	6.33	6.9972	44.2871
I	18.14	103	24	450.77	238.02	8.1	6.33	5.0779	32.1394
J	18.86	104	17	541.80	262.54	8.1	6.33	2.7606	17.4729

Total estimated horizontal maximum acceleration, both at free field station and roof level was plotted; Fig. 8a represents the acceleration level corresponding to every earthquake epicenter position. Also, an evaluation of maximum acceleration at each horizontal sensor was carried out; the results are plotted on Fig. 8b.

These results showed that the maximum accelerations were generated by the closest epicenter to the buildings. It is interesting to mention that maximum acceleration at the free field station was 78 Gals. Waves coming from the eastern epicenter produce accelerations equal to 55 Gals, whereas the western epicenter produced values close to 17 Gals.

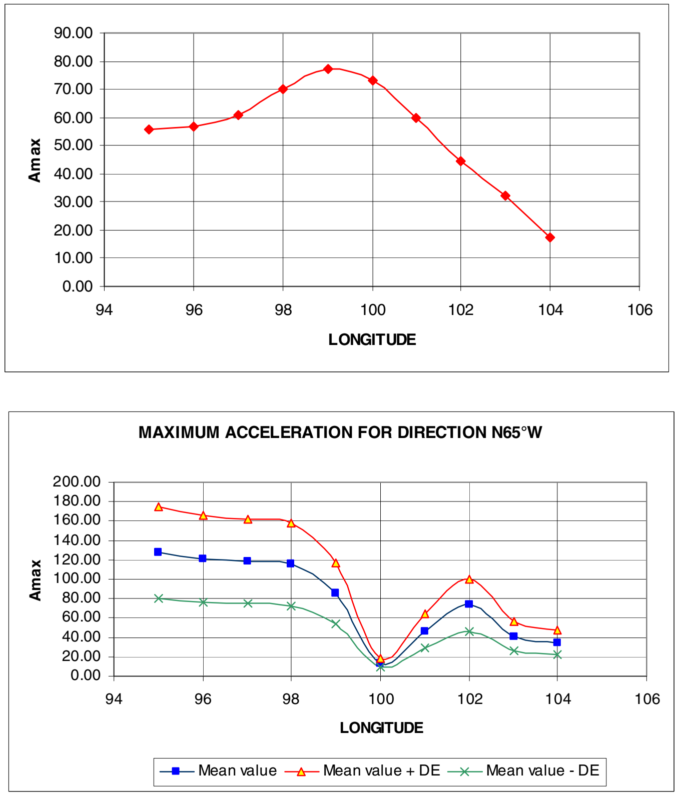


Fig. 8 Calculation of maximum accelerations for the free field station, produced by epicenters along the Mexican south coast

From these values, an evaluation was performed, looking for the maximum acceleration at roof level. Fig. 9 shows the results. They indicated that maximum acceleration at roof level, along (N65°W) direction, were 160 Gals as upper limit, and 80 Gals as lower limit, for earthquake waves coming from a place located at a position, whose latitude was in the 95°- 98° range. Maximum accelerations decreased as focal zones move to the east or to the west of that range, decreasing down to 50 Gals.

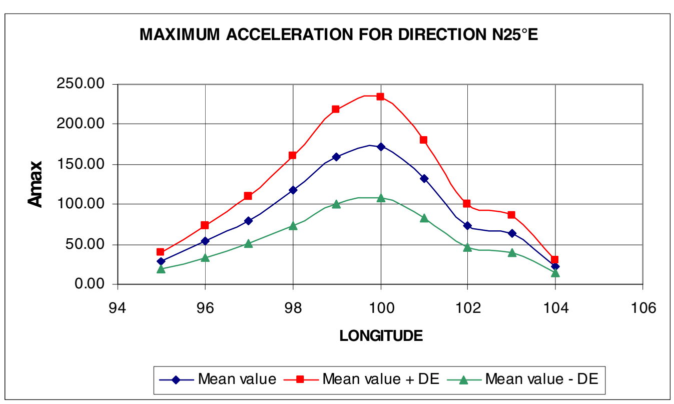


Fig. 9 Evaluation of maximum accelerations on the roof of the building A

On the orthogonal direction (N25°E), acceleration showed a smooth variation as epicenter moves from the most eastern location, from where they produced 40 Gals as maximum acceleration, up to the 95° epicenter location, where seismic motion of the building generated a maximum value equal to 240 Gals. As focal zone moved to the west, accelerations decreased down to 30 Gals, when the focal zone was located at the 104° W location.

PROBABLE EFFECTS ON STRUCTURAL BEHAVIOR

From structural analyses, it was possible to establish that when maximum acceleration at free field reached 85 Gals along the transverse direction (N65°W), and 135 Gals along the longitudinal direction (N25°E), displacements atop the instrumented building reached values lower than 0.012 H, being H, the total height of the building. This limit is set by Mexico City Building Code, as the upper allowable limit for relative displacements at roof level. So, when the worst seismic event might have an epicenter at the closest point at the south coast, with M_s = 8.1, the instrumented building may present motions under the limit set by the Code.

COMENTS

The information retrieved from recorded data during the observation period, gave place to the following comments:

Digital records obtained after 19 seismic events and Fourier Fast Transform of the time series, clearly showed a linear structural behavior of the instrumented buildings, even when a M_s = 7.5 earthquake waves arrived to the buildings. Maximum recorded acceleration level was kept at the 50 -150 Gal level; these values did not exceed limits defined by Van Koten's scale, for very perceptible motions for human occupancy. Displacement level atop the buildings did not change structural stiffness of the buildings, and therefore, no deterioration process was detected at both instrumented buildings. Information produced from the accelerometric network produced an statistical model, from which it is possible to evaluate accelerations at the free field station and at roof level, once the focal zone position is fixed, as well as its magnitude. Evaluation of possible effects produced by virtual earthquakes, generated along the subduction fault at the south coast, at the instrumented buildings by use of the model was carried out. Strong virtual earthquakes produced along the south coast of Mexico, did not surpass allowable displacement levels, set by Mexico City Building Code.

ACKNOWLEDGEMENT

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