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FACTORS CONTRIBUTING TO THE CATASTROPHE IN MEXICO CITY DURING THE EARTHQUAKE OF SEPTEMBER 19, 1985

James L. Beck and John F. Hall

Earthquake Engineering Research Laboratory, California Institute of Technology

Abstract. The extensive damage to high-rise buildings in Mexico City during the September 19, 1985 earthquake is primarily due to the intensity of the ground shaking exceeding what was previously considered credible for the city by Mexican engineers. There were two major factors contributing to the catastrophe, resonance in the sediments of an ancient lake that once existed in the Valley of Mexico, and the long duration of shaking compared with other coastal earthquakes in the last 50 years. Both of these factors would be operative again if the Guerrero seismic gap ruptured in a single earthquake.

Introduction

The Mexican earthquake of September 19, 1985, together with its aftershocks, produced the worst earthquake disaster in the history of Mexico. Mexico City, although not totally devastated, was dealt a major blow in which as many as 20,000 lives may have been lost (BAREPP,1986). About 300,000 people, among a population of 18 million, lost their dwellings, and from 800 to 1000 buildings have been, or will be, demolished. Public buildings, such as schools, hospitals, and some government housing projects, were hard hit, contributing significantly to the large loss of life. The economic impact, although uncertain like many of the statistics related to the earthquake damage, is estimated to be of the order of 5 billion U.S. dollars. From the engineering viewpoint, the most serious aspect of the damage is that over 300 high-rise buildings designed under modern seismic building codes either collapsed or were so severely damaged that they are beyond repair. A survey by engineers from the Institute of Engineering at UNAM (the National Autonomous University in Mexico City) showed that within the zone of damage approximately 20% of the buildings between 6 and 15 stories either collapsed or were severely damaged.

In this paper, we discuss what we feel are the major factors contributing to this unprecedented amount of damage to modern multi-story buildings. Our conclusions are based on a personal inspection of the damaged area of Mexico City two weeks after the earthquake, and on information supplied by our colleagues at UNAM. Much research still needs to be done; in particular, we highlight several factors which are important in understanding the engineering effects of the earthquake and which could benefit from studies by seismologists. In a companion paper (Hall and Beck, 1986), we present an overview of the damage and discuss common weaknesses in design and construction which were revealed by the earthquake.

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Seismological and Geological Background

The earthquake occurred at 7:18 a.m. local time (13h 17m 48s UT) on Thursday, September 19, 1985. It was fortunate that it did not occur later in the day because most of the high-rise buildings that collapsed were office buildings which were practically empty at that time in the morning but which would have been fully occupied later. The shock had a Richter surface wave magnitude of Ms=8.1 and it was followed by a large aftershock of magnitude Ms=7.5 on Friday evening, September 20. The main shock was centered about 400 km from Mexico City on the Pacific Coast, near the town of Lazaro Cardenas on the border between the states of Michoacan and Guerrero. The tectonic source of the earthquake is the subduction of the Cocos plate under the North American plate. This subduction zone has been responsible for several major earthquakes which have shaken the central and southern parts of Mexico this century, including the 1957 Acapulco event (Ms=7.5) and the 1979 Petatlan event (Ms=7.6). Both of these earthquakes also produced serious damage in Mexico City, but not to the extent of the recent earthquake.

A unique seismological feature of the September 19 earthquake, compared with other Cocos subduction earthquakes in the last fifty or so years, is that it consisted of two separate rupture events, each lasting about 16 s. The second event was initiated about 25 s after the first and was located about 90 km southeast of it, with the aftershock zone of the 1981 Playa Azul earthquake in between (Houston and Kanamori, 1986; Eissler, Astiz and Kanamori, 1986). An interesting problem, not yet resolved, is whether this caused shaking of longer duration in Mexico City than would have occurred if the rupture process had been more or less continuous. This has engineering implications, since the duration of strong shaking is one of the factors controlling the amount of damage.

A feature of over-riding importance in an explanation of the damage is the local geology in Mexico City. Much of the city is built on the edge of a lake bed, which has been dry since the lake was drained in early colonial times. Sediments deposited by the lake produced a subsurface soil profile consisting of roughly horizontal layers; a relatively firm layer of gravel and fill at the surface which is 5 m to 10 m thick, with an approximate effective shear wave velocity c = 90 m/s, an underlying soft clay layer which is 25 m to 35 m thick, with c = 57 m/s, and beneath that, a firm sand layer, 2 m to 5 m thick, with c = 150 m/s. There are also deeper layers of clay and sand. The soil profile data is based on information from boreholes at construction sites supplied by Professor Meli of UNAM. The effective shear wave velocities were calculated from the data in Zeevaert (1964). He gave values for one particular site on the lake

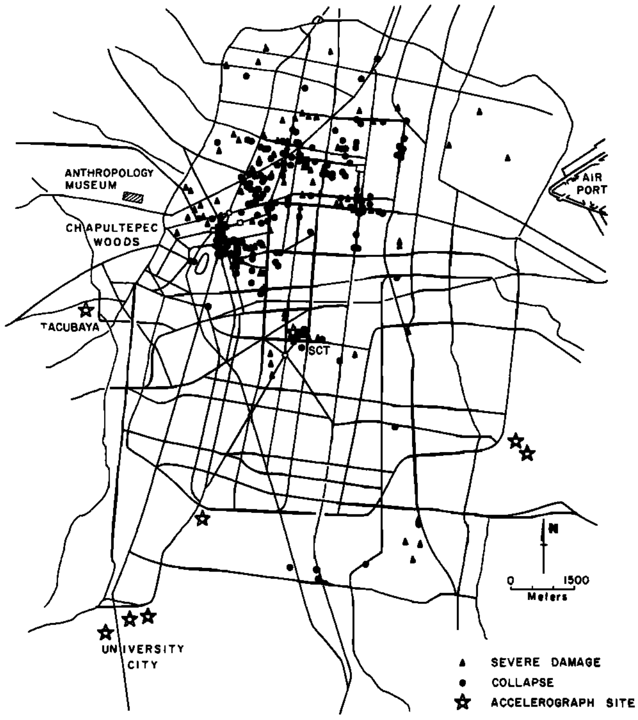

Fig. 1. Distribution of severe structural damage and sites where records of the strong ground shaking were obtained. Only some of the major streets of Mexico City are drawn.

bed, but since the sediments were probably deposited fairly uniformly, the above values for the clay and sand layers are likely to be representative over horizontal dimensions of several kilometers.

Factors Contributing to the Damage

Based on a survey by engineers from UNAM, a map has been drawn showing the distribution of severe damage and structural collapse throughout Mexico City (Figure 1). It is of great interest that this damage is confined to those portions of the city which are on the old lake bed. The same survey showed that percentagewise most of the damage occurred to buildings with 6 to 15 stories. Because of the severity of the structural damage, there has been speculation that it is the result of poor quality materials, poor workmanship and lack of adherence to the earthquake-resistant design provisions of the Mexican building code. These factors may have played a role in some cases, but in our judgement, the major reason for the extensive damage was that the intensity of shaking on the lake bed was much greater than the intensity upon which the seismic provisions of the building code were predicated. The two major factors behind the severity of the seismic attack on buildings were:

(1) resonance in the lake sediments,
and (2) the long duration of the shaking.

Resonance of the Lake Sediments

A strong-motion record obtained during the main shock at the Seismological Observatory at Tacubaya (Figure 2) is representative of several strong-motion records obtained on firm ground in Mexico City. They exhibit a broad-band frequency content and peak horizontal accelerations of 3% to 4% g. In contrast, a strong-motion record obtained at the SCT site (Ministry of Communications and Transport) on the lake bed shows a peak horizontal acceleration of 17% g and a frequency content dominated by a component with a period of 2 s (Figure 3). Actually, the maximum resolved acceleration from the east-west and north-south components is 20% g. This can be compared with that corresponding to a 100-year return period, which was estimated prior to the earthquake to be 14% g (Rosenblueth, 1979). The vertical accelerations at the SCT site were much smaller, with a peak about one-fifth of the maximum horizontal accelerations. Another characteristic of the lake bed motions is that the acceleration amplitude continued to grow over about 40 s, suggesting a resonant build-up within the sediments.

Further support for this resonance hypothesis is the strong amplification of the ground motions between the Tacubaya and SCT sites, which are separated by 5 km (Figure 1). This shows up very dramatically in the response spectra for these two sites (Figure 4). The response spectrum shows the maximum response to the ground motion reached by an elastic mass-spring oscillator as a function of the vibrational period of the oscillator. For a 5% damped oscillator, which can be taken as representing the elastic response of a building in its fundamental mode of vibration, the peak response to the SCT ground motion is about 25 times larger than the peak response to the Tacubaya ground motion at a period of 2 s. In fact, the spectral acceleration of 1g for 5% damping is exceptionally large. Notice that the Tacubaya spectrum does not have a peak at a period of 2 s, suggesting that the strong response at this period on the lake is a local effect. In fact, Houston and Kanamori (1986) find that the source Fourier amplitude spectrum is somewhat depleted in the 1 to 10 second range relative to the average source spectrum of 7 large interplate subduction events.

There are two other features of the SCT response spectrum in Figure 4 worthy of comment. The side peak at a period of 2.6 s seems to be a significant feature. It also shows up in the Fourier amplitude spectrum at 0.38 Hz (period 2.63 s), where it is more clearly separated than in Figure 4 from the peak at 0.49 Hz (period 2.04 s). The other peak in the SCT response spectrum around 0.5 s (Figure 4), actually appears at 0.68 s when the spectrum is recalculated with a finer frequency resolution. There is a corresponding peak in the Fourier amplitude spectrum at 1.47 Hz (0.68 s), although it does not appear as strongly as in the response spectrum.

There are two simplified models which could

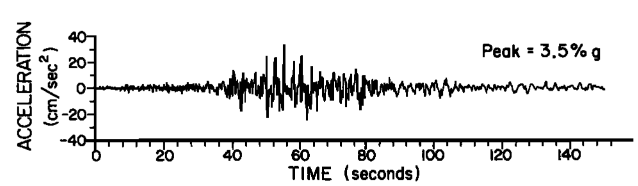

Fig. 2. Ground acceleration in the east-west direction recorded at the Seismological Observatory, Tacubaya, which is on firm ground. (Trigger time: 13:19:09 UT).

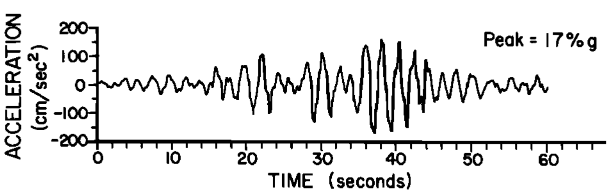

Fig. 3. Ground acceleration in the east-west direction recorded at the SCT site on the old lake bed. (Trigger time: 13:19:43 UT).

explain the apparent resonance phenomenon, one involving body waves propagating up through the valley sediments and the other involving surface waves propagating across the valley. The real situation is sure to be more complex, although a combination of these models may give at least a qualitative explanation. We feel, however, that the phenomenon is important enough to warrant much more detailed studies than the simplified picture given below.

The body-wave model hypothesizes that shear waves enter the Valley of Mexico from the basement rock and as they propagate towards the surface, they encounter layers of sediment with lower wave velocities. This causes the waves to approach vertical incidence, so that resonance is caused by reflections back and forth between the free surface and any interface across which there is a pronounced change in the shear wave velocity. The largest such change near the surface is at the interface between the shallowest clay layer and the sand layer beneath it. The lowest frequency resonance in this situation would occur for shear waves which have a period four times the time it takes to propagate from the clay/sand interface to the free surface. At the SCT site, the surface layer is about 6 m thick and the clay layer beneath is 25 m thick. From the shear wave velocities given earlier, we find that the lowest resonant period is 2.0 s. The next lowest resonant period for these two layers is 0.67 s, one-third of the fundamental period. These resonant periods are in excellent agreement with the peaks seen in the spectra of the SCT strong-motion record. Based on a similar argument, the 2.6 s peak may be due to resonance set up between the free surface and the next deepest clay/sand interface.

For the surface-wave model, it is not necessary to postulate the excitation of "cross-valley" modes to get greatly amplified surface motions. Indeed, the existence of strong standing waves set up by reflections across the valley seems unlikely. Drake (1980), using a finite-element model, showed that Love and Rayleigh waves propagating into a semi-infinite "valley" are still greatly amplified at certain periods despite the absence of a reflecting boundary. The periods for large amplifications correspond to the longest resonant periods of shear waves propagating vertically into the relatively soft alluvium layer at the surface. Thus, the agreement between the resonant periods from the vertically-incident shear-wave model and the periods of the peaks in the strong-motion spectra does not necessarily favor this model over the surface-wave model.

The importance of the resonance phenomenon in contributing to the structural damage is apparent from the response spectra comparison in Figure 4. It is the reason why the damage was confined to areas of Mexico City on the lake bed. It also explains why high-rise buildings suffered the most severe seismic attack. They have long fundamental periods of vibration and hence responded resonately to the long-period lake-bed shaking. The old colonial buildings and other low-rise buildings survived with little damage primarily because they have short fundamental periods and not because they are relatively stronger.

A cursory examination of Figure 4 might suggest that buildings of about 15 to 25 stories would have suffered the most severe damage, based on the rule of thumb which states that high-rise buildings with N stories have elastic fundamental periods approximately equal to N/10 s. In fact, the statistics show that the damage was concentrated in buildings of 6 to 15 stories. The explanation is that as a building yields and suffers damage to its nonstructural and structural components, its natural periods lengthen. In effect, buildings with 6 to 15 stories were drawn into the most energetic frequency band of the lake-bed motions, whereas taller buildings moved out of this range as they became more flexible during the earthquake (Hall and Beck, 1986).

Duration of Shaking

Assuming the amplification occurring on the lake bed is primarily due to a resonant build up of seismic waves within the top subsurface layers, the duration of the incoming seismic waves is a very important factor in controlling the degree of the amplitude build-up. The longer duration of the main shock on September 19, 1985 compared with other earthquakes in the Cocos subduction zone in the last 50 years, therefore helps to explain the greater amount of destruction in Mexico City. First, the ground motions had more time to build up to larger amplitudes by resonance within the lake sediments. In fact,

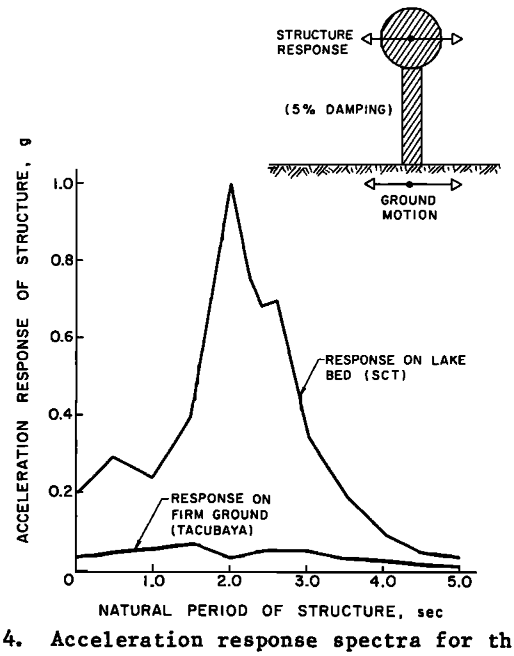

Fig. 4. Acceleration response spectra for the Tacubaya and SCT strong-motion records shown in Figs. 2 and 3. The oscillator has a damping of 5% of critical.

this may have been more important than the increased amplitude of the incoming waves due to the larger magnitude of the recent event compared with previous coastal earthquakes. Second, once structural damage is initiated, it tends to progressively worsen as the number of large-amplitude cycles increases, so for longer shaking, more damage will accumulate.

Concluding Remarks

Although we feel that the principal reason for the extensive damage in Mexico City was that the shaking was much more intense than the writers of the building code had anticipated, there were also instances of undesirable design and construction practices (Hall and Beck, 1986). Also, it is important to note that prior to the earthquake, the seismic provisions of the building code for Mexico City would have been considered adequate by most experts. It was known from earlier strong-motion earthquake records obtained in Mexico City that the ground motion is substantially altered by the sediments of the lake over a certain frequency range (Zeevaert,1964). This was taken into account in the building code for Mexico City in that the most stringent design requirements were for structures in the period range from 0.8 s to 3.3 s which were to be built on the lake bed. In contrast, U.S. codes take advantage of the fact that all strong-motion records obtained in this country show that the energy in the spectrum of the ground motion peaks at shorter periods, so the seismic codes become progressively less stringent for buildings with periods which exceed about 0.3 s.

Thus, one of the two major factors contributing to the unexpectedly large motions, the resonance of the lake sediments, was not a surprise. What was surprising was the degree of the amplification, and the second major factor, the long duration of shaking, may have contributed significantly to this. With these two factors in mind, the Guerrero seismic gap to the south-east of the September rupture zone must be viewed with considerable concern. Should this gap rupture completely in one earthquake, it appears to be capable of producing an event of a similar size and similar duration of shaking to last year's rupture of the Michoacan gap. In addition, the Guerrero gap is closer to Mexico City. The conclusion is that lake bed motions at least as intense as those in September must be considered as being a strong possibility in the near future.

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J. L. Beck and J. F. Hall, Earthquake Engineering Research Laboratory, Caltech,
Pasadena, CA 91125

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