THE SEPTEMBER 1985 MEXICO EARTHQUAKE

PRELIMINARY REPORT OF THE NEW ZEALAND RECONNAISSANCE TEAM

1. PREFACE

A major earthquake on the Pacific Coast of Mexico on 19 September 1985 caused considerable damage to Mexico City and in the epicentral region.

As a consequence, Ministry of Works and Development, Department of Scientific and Industrial Research and the New Zealand National Society for Earthquake Engineering decided to mobilise a joint reconnaissance team to visit Mexico. The aim was to examine the damage first hand to determine whether New Zealand seismic design procedures and practice provide for proper defence against major earthquakes of this kind. In addition, it was felt by the NZNSEE that it was a good opportunity to obtain first hand experience in mobilising and maintaining a reconnaissance team in the field. The members of the team were Architect Warwick Massey, Engineers George Butcher, Tony Gillies, David Hopkins, Rob Jury, Garry McKay and Engineering Seismologist Graeme McVerry.

This preliminary report is a brief account of observations made and of information gathered during the team's visit to Mexico City and the epicentral region. A more detailed reconnaissance report is to be published by NZNSEE early next year. We wish to acknowledge the assistance given to us during our stay in Mexico by the Institute of Engineering, University of Mexico and in particular Ing. Jorge Prince who supplied reports and publications covering codes and also by the New Zealand Embassy in Mexico City, particularly Ms Caroline Forsyth, the First Secretary.

2. INTRODUCTION

At 7.18 a.m. local time on 19 September 1985 a major earthquake of magnitude 8.1 occurred in the subduction zone along the Pacific Coast of Mexico (Fig. 1) near the mouth of the Rio Balsas which forms the border between the States of Michoacan and Guerrero. Extensive damage was caused 400 km from the source in the central part of Mexico City which is situated on highly compressible clay deposits of an old lake bed, long recognised as exhibiting soil layer resonance under earthquake excitation. There was also substantial damage to specific structures in the epicentral region (Fig. 2) at locations including the new industrial town of Lazaro Cardenas, the luxury resort of Ixtapa, and the towns of Playa Azul, Zihuatanejo and Petatlan. North of the epicentral region, the towns of Coalcoman and Ciudad Guzman and its neighbouring village of Gomez Farias were heavily damaged, while to the south the state government buildings and church in Chilpancingo were also affected. There was virtually no damage in Acapulco, although the economy of the city was hard-hit by the absence of tourists from the resort hotels in the month after the earthquake.

A major after-shock of magnitude 7.5 at 7.37 p.m. on 20 September caused further damage, including collapse of several buildings which had been damaged in the main shock 36 hours earlier. There were numerous felt aftershocks in the two weeks after the earthquake.

The damage in Mexico City was certainly massive, but concentrated in a relatively small zone (a portion of the old lake bed) of a very large city with a total population of 17 million. The current official death total is about 4,000. With the large number of collapsed schools and office buildings, the toll would have been many times higher if the earthquake had struck in mid-morning. In an urban area of 1,050 km^2, the zone containing a large number of collapses and severe damage was confined to an area of 23 km^2, within a total damage area covering about 65 km^2. Even in the worst hit zones damage was far from universal, with complete city blocks escaping largely unscatched. In most parts of the city there was little visible evidence of a major earthquake. The New Zealand reconnaissance team arrived in Mexico City on Saturday, 4 October, 16 days after the earthquake. The last rescue operations ceased that day, although demolition, clean-up work and repairs continued.

In the Pacific Coast region, the surprising feature was the lack of widespread damage. The general impression was not that of being in the epicentral region of a magnitude 8 earthquake, as town after town of unreinforced brick and adobe construction escaped with only minor cracking. Mainly larger structures appeared to be affected, although the accelerograph records in this zone show considerable short period content as well as long periods.

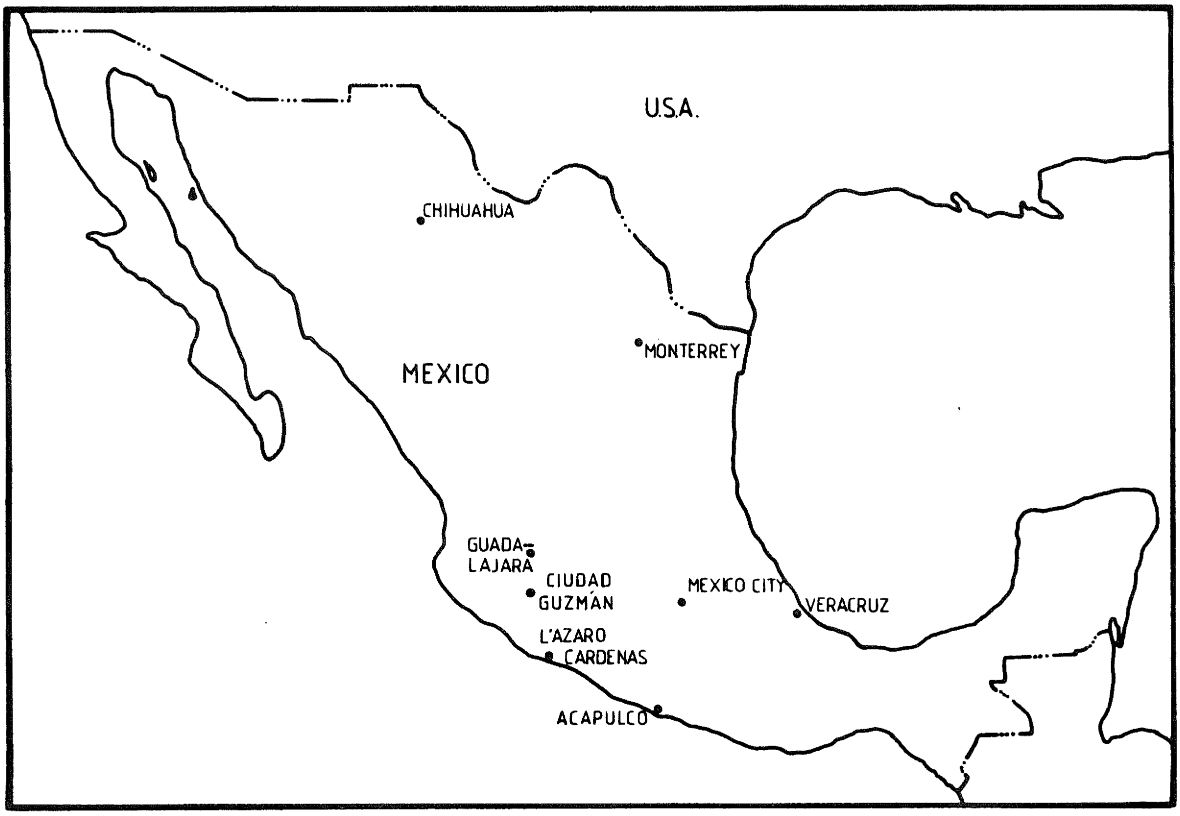

Figure 1 : Map of Mexico

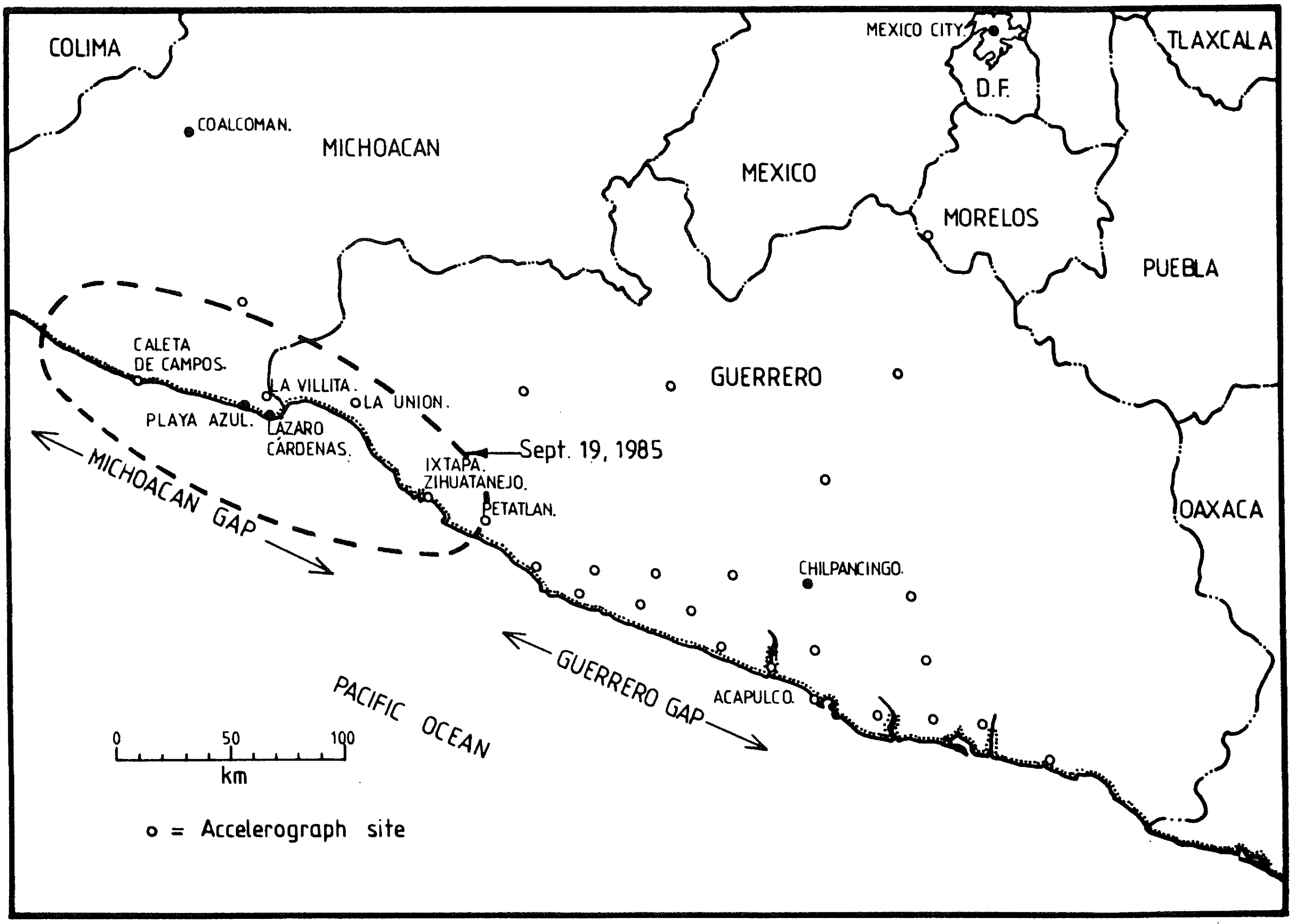

Figure 2 : Map of Epicentral Region

In the town of Cuidad Guzman north of the epicentral region many one and two-storey houses had collapsed, but other towns in the area appeared largely unaffected.

3. SEISMOLOGY

The earthquakes of September 1985 occurred along the Pacific Coast of Mexico where the Cocos Plate is subducting under the North American plate at a convergence rate of about 75 mm/year. The subduction zone stretches over 1,350 km, with a recurrence period for large (Ms 7.0) earthquakes of about 30 to 70 years along much of this length [1]. There have been 33 earthquakes this century exceeding magnitude 7.0 between Jalisco and Oaxaca, the part of the subduction zone giving rise to earthquakes which can damage Mexico City.

Preliminary estimates of the epicentre of the 19 September 1985 main shock have shown considerable variation, one estimate placing it off the mouth of the Rio Balsas at 17.68 N and 102.47 W and others locating it onshore. The fault plane is located at depth, probably in the 15 to 30 km range, with a focal depth certainly less than 33 km, so there have been no reports of surface faulting. The earthquake ruptured a very large fault area for a Mexican subduction zone event. UNAM seismologists Singh and Castro estimated a rupture possibly up to 200 km long and 80 km wide with a maximum fault displacement exceeding one metre [2].

The main shock occurred in the Michoacan gap, an area previously considered to be seismically inactive because no major earthquakes have occurred there for at least 180 years, a period far exceeding the usual return period of 30 to 70 years for most of the subduction zone. Conversely, the neighbouring Jalisco gap to the north and the Guerrero gap to the south are considered to have a high potential for a large earthquake at present in that they have experienced large events in the past, but with a gap since the last one of the order of the usual recurrence interval [1]. The strong-motion array under installation at the time of the earthquake was primarily intended to record the large earthquake expected in the Guerrero gap in the next 10 years [3]. The likelihood of a major earthquake in the Guerrero gap in still considered very high.

The main event appeared to be a double shock with an initial energy release near Caleta de Campos close to the northern end of the rupture zone followed about 20 seconds later by a second burst of energy south of La Villita near La Union. The extreme rupture length, multiple events and wave dispersion over the propogation distance to Mexico City contributed to the long duration of shaking which was so damaging there.

Strong-Motion Accelerograph Records

The ground motion in the coastal region near the epicentre was recorded on a new network of digital accelerographs, the Guerrero accelerograph array [3-6], which had 20 of its planned 30 stations installed at the time of the earthquake. The array was designed to record strong ground motion on bedrock from large subduction zone earthquakes in the Guerrero gap and to a lesser extent the Michoacian gap. The array produced records from 15 stations. There were also a few other instruments in the epicentral region installed independently of the array. Processing and publication of the records by UNAM and UCSD have been very rapid, demonstrating a great advantage of digital instruments over film recording accelerographs.

In the main shock, peak accelerations of 0.12g to 0.17g were recorded at 5 array stations, 4 of which were sited over the rupture area. Peak accelerations exceeding 0.1g were recorded at 2 stations in the largest after-shock, with a maximum acceleration of 0.2g. A non-array instrument at Zacatula situated on compacted clay in the delta zone of the Rio Balsas, 9 km from the steel mill at Lazaro Cardenas, recorded a peak acceleration of 0.27g, more than any of the rock-based instruments of the Guerrero array.

The spectra in the epicentral region were generally broad-band between about 0.1 and 3 Hz, with no predominant frequency. They contained short period accelerations as well as the long period ones which dominated the Mexico City record. The 5% damped absolute acceleration spectrum for the NS component of the Zacatula record peaked at just over 1g at a period of 0.34 seconds. The response spectra from the rupture zone were generally similar in shape to the well known Taft record in the 1952 Kern County earthquake, although possibly with higher response velocities at long periods. The Guerrero records were the first obtained within the rupture zone of a magnitude 8 earthquake.

The shaking was also recorded in Mexico City at 15 strong-motion accelerograph stations sited on a number of different ground conditions [7]. An instrument on volcanic rock at University City [8] gave a maximum acceleration of 0.04g, with a strong 2 seconds period content which is unusual for this type of ground. The acceleration was much amplified in the old lake bed zone, which has long been noted for showing text-book examples of soil-layer resonance. The accelerograms recorded on the deep soft soils of the old lake bed are characterised by very long dominant periods, about 2 seconds at the SCI (Secretaria de Comunicaciones y Transportes) [9] and 3.5 seconds at the Central Produce Market [10]. There was extensive damage at the SCI compound, including several partial collapses of office buildings. The peak acceleration in this record was 0.20g, strongly polarised in the N60E direction. More importantly, an amplitude of about 0.1g of near-sinusoidal motion was maintained for more than 22 seconds or 11 cycles of 2 second period. It was the duration of this long-period motion, associated with large displacements (21 cm ground displacement at SCI), that was probably responsible for the extent of damage, rather than the peak accelerations. The peak accelerations were not exceptional compared to other earthquakes around the world.

Many of the seriously damaged buildings would have started responding with periods much less than two seconds, but as damage to infill panels occurred and frames softened, the structural periods would lengthen and would move towards the spectral peak of the motion. In most earthquakes other than those in Mexico City, a period lengthening shifts the response to a less energetic part of the spectrum rather than to the peak.

While many useful records were obtained from this earthquake, there were also a number of disappointments. In previous years there have been accelerographs in the Central City area, in the National Lottery Buildings and Alameda Park, close to the heart of the most damaged zone. These instruments have now been removed or were non-operational because of lack of funding for maintenance. While there were several badly damaged structures in the immediate vicinity of the SCI centre, it is several kilometers south of the Central City area. Likewise, an operational instrument at Nonoalco would have produced very interesting records, given the damage in the neighbouring Ilatelolco, north of the centre of the City. It was also disappointing that there were no instruments to measure the response of structures. All were aimed at obtaining ground or basement accelerations.

4. SEISMIC DESIGN PROVISIONS IN MEXICO

4.1 Code Status and Implementation

Under the 1917 Constitution, Mexico became a Federal Republic comprising 31 states and a Federal District which contains a major part of the capital, Mexico City. Mexico City contains over one sixth of the country's population and a large proportion of the engineered structures. The states have complete autonomy on local matters and this includes the responsibility for formulating building codes including seismic provisions. In contrast the Federal District is effectively under the control of the President through the Chief of the Federal District.

The authority responsible for drafting codes and for issuing construction and occupation permits in the Federal District is the Federal District Department. Responsibility for complying with code provisions is usually placed with the registered engineer or architect who is awarded the construction licence, and thus department engineers rarely check computations and drawings except in special circumstances [11].

A great deal of freedom has thus resulted in the design and supervision of construction of privately owned buildings. This has led to a tendency for building codes to be regarded by Mexican engineers more as guidelines rather than rigid regulations. In legal disputes however ignorance or violation of the code requirements has usually greatly weakened the designer's position [11].

4.2 History of Development of Seismic Design Provisions in the Federal District (Mexico City)

The first regulations relating to seismic design in Mexico City were established in 1942. These regulations required that buildings 15 m or greater in height be designed to resist a uniform horizontal acceleration of 0.025g [7].

Following the 28 July 1957 earthquake which caused severe damage in Mexico City emergency regulations [12] were drafted which remained operable until a new code was introduced in February 1966. The emergency regulations were applicable for all new buildings lower than 45 m in height. New buildings having a total height greater than 45 m were required to be subjected to special study. Three different subsoil conditions were recognised, namely lake zone, transition zone and hilly zone (Fig. 3), and buildings were classified in terms of usage and structural type. A base shear coefficient was introduced as a function of type, useage and zone. The distribution of load with height was triangular. Accidental eccentricities of 5% of the maximum building dimension were allowed for. Limit state type design methods were provided for with load factors of 1.2 in flexure and 1.5 in axial compression for concrete structures and 1.0 in flexure and 1.3 in axial compression for steel structures. Maximum relative displacements under the code load distribution calculated using gross section properties were limited to 0.002 times the differences in elevation. Separate studies were required to determine separations to avoid pounding.

The provisions for earthquake resistant design introduced in 1966 [13] made several changes to the emergency regulations issued eight years previously. Firstly, the soil classification was reduced from 3 zones to 2; a zone of high compressibility and a zone of low compressibility.

Base shear coefficients were amended resulting in large reductions in base shear for important structures situated in the lake zone. A reduction in the overall load factor for limit state design also resulted, with 1.2 used typically. Three methods of analysis were introduced. For predominantly shear wall type structures satisfying given limits for aspect ratio, and structural layout, a simplified method was allowed. Under this method no check was required of lateral displacements, torsions or overturning moments.

For other structures, either an equivalent static analysis or a dynamic analysis was permissible.

Drift limitations were as follows:

0.002 - where non-structural elements were not separated;

0.003 - where non-structural elements were separated in important structures situated in the zone of compressibility;

0.004 - elsewhere.

For other structures, eg: office buildings, where non-structural items were separated, no limitations were imposed. Separations consistent with the displacements resulting from the equivalent static method were required. Additional requirements were also provided for separation at boundaries. In the zone of high compressibility for example, the separation was required to be not less than the maximum lateral displacement calculated using the equivalent static load distribution at any level plus 0.006 times the elevation of that level.

The 1977 version of the seismic loadings code [14] (current until the earthquake on the 19th Septemeber 1985) differed from its predecessors in several respects. These differences included requirements of ductility, and the use of design load values based on a probabilistic assessment of seismicity. Under this version structures are classified into three important groups in a similar fashion to that set out in the 1966 code. Structures are also classified in accordance with their structural form. Four types are defined:

Type 1: Structures in which lateral forces are resisted at each level by specified structural systems or combinations of systems

Type 2: Tanks

Type 3: Retaining walls

Type 4: Other structures

Typically three different design spectra are given covering three ground conditions, namely: firm ground, Zone I, transition soils, Zone II, and soft soils, Zone III.

The spectra defined are elastic spectra being reduced to design values through the use of a reduction factor based on an assessed ductility factor listed in the code. It is important to note that ductilities of up to 4 can be assumed under the provisions of this code with no special requirements for detailing for ductility. A ductility factor of 6 is possible if some ductile detailing similar to that set out in Appendix A, ACI 318 [15] is carried out. It would appear however that many engineers have accepted the higher load levels resulting from the use of a ductility factor of 4 rather than comply with the additional detailing requirements. The use of a load factor of 1.1 is implied by the level of seismic base shear coefficient.

Under the provisions of the code one of these analysis methods is to be used, the choice depending upon the height and complexity of the proposed structure. Structures with height less than 60 m can be analysed using either the equivalent static or dynamic methods. For higher structures, a dynamic analysis must be performed. A simplified analysis can be used for predominantly wall type structures satisfying several aspect ratio requirements and with height not greater than 13 m. A capacity design approach is not required.

Three limit state requirements relating to prevention of damage due to excessive drift are included. The first limits drift to 0.008 except where non-structural elements are fully separated from the structure when the limit is increased to 0.016. Deformations are calculated using the reduced design spectra scaled up by the full ductility factor. The second requires provision for glass panes to move in window frames and the third provides limits for separation at boundaries or at joints in structures.

Separations at boundaries are required to be at least the calculated horizontal displacement plus 0.001, 0.0015 and 0.0020 times the height for Zones I, II and III respectively.

Following the severe shaking experienced during the earthquakes of 19 and 20 September 1985, several deficiencies in the 1977 provisions were recognised and amendments have been made in the emergency regulations promulgated on 18 October 1985.

The emergency regulations have set new seismic coefficients for Zones II and III which are respectively in the order of 35% and 70% greater. In addition, the implied ductility factors have been reduced from 6.0 to 4.0 and from 4.0 to 2.0 as applicable. The increase in design load when seismic detailing requirements are ignored is therefore more pronounced. Drift limitations calculated using these increased loadings remain unchanged.

Flat slab type structures proved very flexible and in recognition of this the stiffness contribution of the slab has been reduced by reducing the width of the "beam" strip and taking half of the column stiffness in the equivalent frame analysis.

These emergency regulations are to be applied to all new construction and also to all repair work that is undertaken.

4.3 Materials Codes

In the Federal District, materials codes have been established for Reinforced Concrete, Masonry, Timber and Steel. These tend to follow accepted international practice, eg: ACI 318 for reinforced concrete [15].Ingeneral, however, there seems to be no special requirements for seismic design except for those set out in the 1977 code for use with a ductility factor of 6.0.

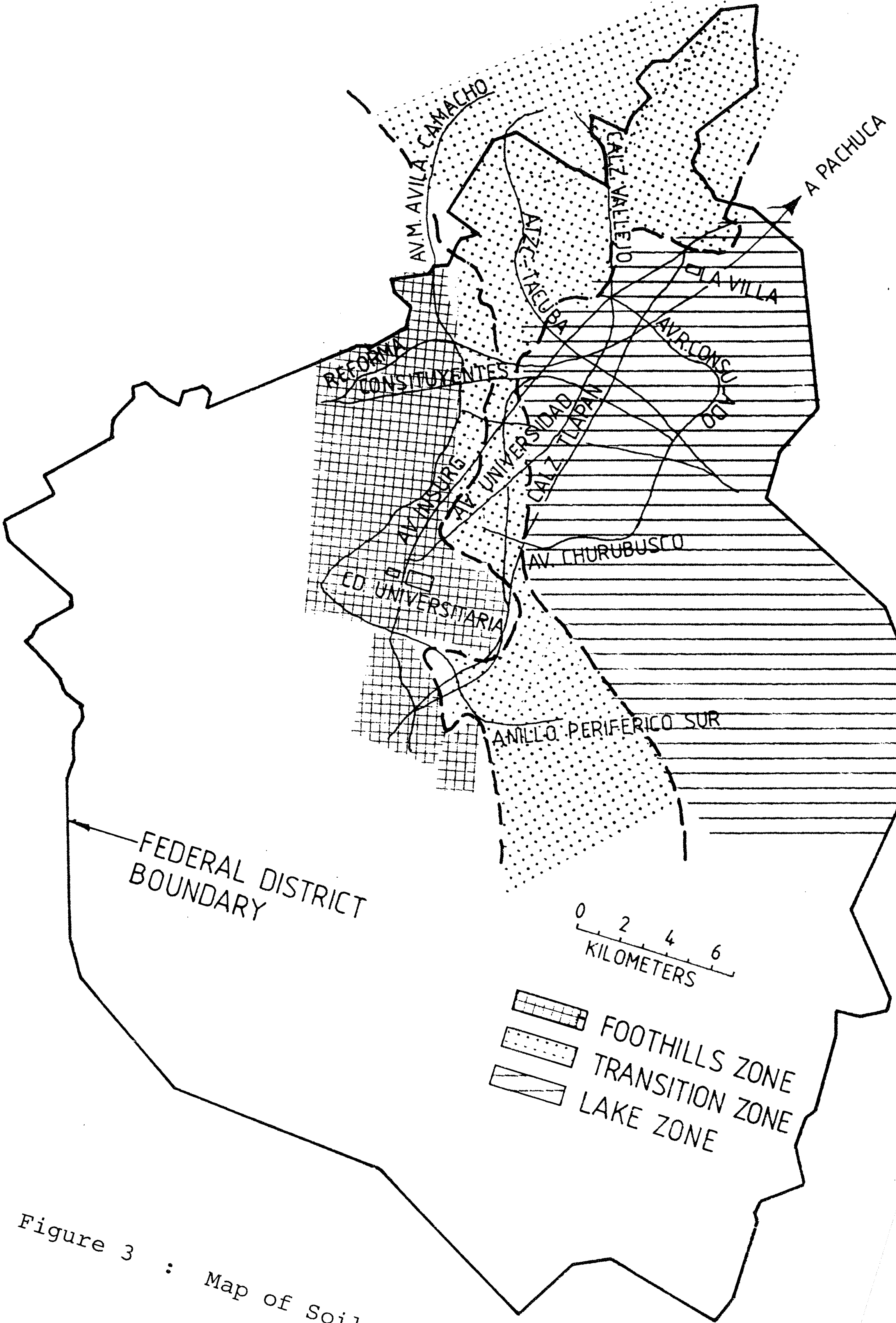

Figure 3 : Map of Soil Zones, Mexico City

5. FOUNDATIONS

5.1 Soil Conditions

Mexico City has been built over two quite different foundation zones with a transition zone between them (Fig. 3). According to Marsal [16] the original development of the City occurred in the western region of Lake Texcoco where the clays are highly plastic, compressible soft soils with natural moisture contents (the most characteristic parameter of the soils) which vary from about 100 to 400 percent. A harder sandy clayey layer about 3 m thick lies at depths from 25 to 35 m while a further hard sandy layer lies at a depth of about 50 m. The water table is commonly one metre below the surface.

Later the City growth extended westwards over the foothills of the Sierra de las Cruces where hard soils and lava predominate. In between these two zones a transition zone where clayey layers of lacustrine origin alternate with erratically distributed sandy alluvial deposits [16].

5.2 Common Foundation Types

Foundation types are chosen to suit the type and size of building. Types include rafts, compensated rafts, friction piles, and end bearing piles to upper or lower firm layers. Some examples of a compensated raft giving relief to piles were observed. It was reported that up to 5 or 6 storey buildings have compensated raft foundations.

Most major structures are founded on end bearing piles taken down to the upper harder layer.

5.3 Settlement

The extraction of water from aquifers under the City and the presence of fill and construction loads have caused considerable sinking of the City [16].

General settlement and differential settlement of significant proportions is evident in many buildings. This is particularly true of the older masonry structures of up to 4 storeys. Even so, some of the more modern buildings show signs of settlement and tilting under gravity loads.

5.4 Lateral Loads

It appears that designs allow for lateral loads to be taken out by passive pressure on foundation walls, or by pile flexure. No clear indication was given as to the way in which adjacent buildings affect this, in terms of contribution to resistance or separation requirements at ground level.

5.5 Effects of September 1985 Earthquakes

The following effects were observed:

- Differential settlements of up to 500 mm were numerous. These were usually in the short direction of buildings but in one case, in the long direction. The effect was observed in buildings of 6 - 12 storeys.
- Uplift of the foundation slab or pile cap combined with settlement of the ground surrounding piled structures. Relative displacements were generally 150 - 200 mm. Slender structures were the worst affected.
- One case of complete pile pull-out with resulting building over-turning was reported.
- Buckling of ground slabs, pavements, etc. as evidence of relative displacements of buildings at ground level. (Fig. 26).

In many cases structural failure prevented foundation damage by acting as a fuse. Given the energy absorbing capability of foundations and the vulnerability of load-bearing elements (columns or walls), this sequence is unfortunate.

Low rise buildings, presumably on raft, compensated rafts or footings suffered little damage. In cases observed of differential settlement, it was difficult to determine whether such movement took place as a result of the earthquakes.

6. STRUCTURAL DAMAGE

6.1 General

The dominant construction material in Mexico for engineered structures is reinforced concrete. There are only a few steel structures. Consequently, most of the damaged structures are of reinforced concrete, but there were nevertheless steel-framed building failures, some of which are discussed in this report. For non-engineered structures (eg: single-storey dwellings) the observed damage was surprisingly slight despite the fact that they are typically constructed of baked bricks and mortar with a plaster finish, or adobe, with minimal lateral load resistance. Even in the city of Lazaro Cardenas, which is located on the coast less than 30 km from the earthquake epicentre, the damage to housing was minimal, whereas some structures of two or more storeys had collapsed or were severely damaged.

6.2 Damage in Mexico City

Mexico City covers an area in excess of 1000 km^2. Within this area damage to buildings was confined to an area of approximately 65 km^2 with a zone of approximately 25 km^2, where collapse or severe damage to buildings occurred. These two zones are shown in Fig. 4. The area of extreme damage or collapse however encompasses the central city zone in which many of the Government buildings are located and so it was the very heart of the city which was hit. As an indication of the extent of damage the following data was obtained from the office of Secretary General of Building Construction on 16 October 1985 (this data was being revised

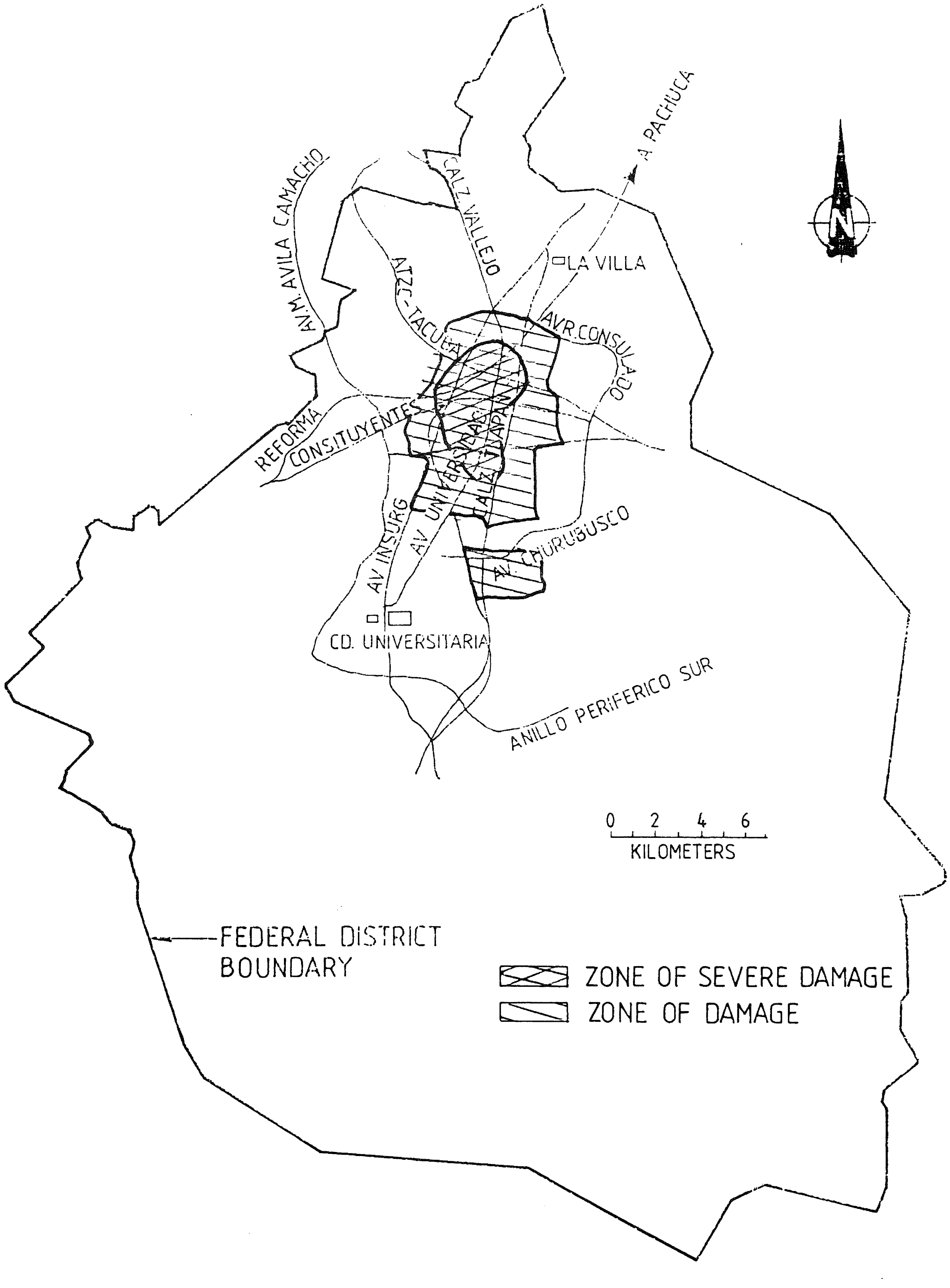

Figure 4 : Damage Zones, Mexico City

Category	Not to be Used*	Usable if Repaired	Usable
Public Buildings	68	27	39
Schools	372	115	800
Health Centres	10	15	28
Cinemas and Theatres	38	18	43
Buildings and Apartments	449	643	652
Sports Centres	3	1	7
Markets	8	5	99
Bridges		1	

(* "Not to be Used" does not necessarily mean collapsed or damaged - some structures were so classed either because the loss of potable water supply rendered them unsuitable for occupancy, eg: schools, or because they could have been threatened by the possible collapse of an adjacent structure. In the schools category, 25 were classed for reconstruction although not all 25 had been damaged).

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daily as the number of post-earthquake inspection reports filed increased and as circumstances changed).

Although many structures were damaged, it is important to keep this in perspective. There are more than 1.5 million structures in Mexico City.

The observed effects of the earthquakes provided clear examples of almost every known cause of poor seismic performance, especially in multi-storey construction.

These included:

- Inadequate member strength and lack of ductile capability.

  Numerous instances of complete disintegration of reinforced concrete columns were evident, due to the opening up of column ties and loss of confinement as a result of removal of concrete cover due to hinging or shear and the unfolding of 90° hooks to ties. As a result, longitudinal bars buckled, core concrete fractured and the gravity load carrying capacity at the column was lost (Fig. 5). In beams, similar effects were observed in 'hinge' regions. The use of 90° hooks to column ties and stirrups rather than 135° hooks appears to be almost universal in Mexico. Several examples of apparent compression failure in columns were also observed. Fig. 6 illustrates one example of beam column joint failures leading to partial collapse of a reinforced concrete office building and Figs. 7 and 8 show damage resulting from apparent column failures.

  One of the most spectacular failures in Mexico City was the collapse of one of the Pino Suarez Towers. Prior to the earthquake, this complex consisted of five buildings in a row. The end two were of 14 storeys and the central three of 20 storeys. The columns were box sections fabricated from steel plate and the beams were truss members. In the short direction (2 bays) lateral resistance was provided by frame action between the beams and the columns. In the long direction (4 bays) "K-bracing" had been provided in one bay. Failure occurred at the third floor level (immediately above the podium), the mode being local buckling in the flanges of the column assisted, perhaps, by weld failure, resulting in complete collapse of one of the 20 storey towers on to the adjacent 14 storey structure. Severe hinging was also observed in the long direction in the beams where the infill panels had braced part of the beam span forcing it to behave as a short coupling beam. Fig. 9 shows the remaining towers with the collapsed structures, partially removed, in the foreground. Figs. 10 and 11 show local buckling in column plates and instances of weld failure and lack of fusion of fillet welds to a diaphragm plate at a beam column joint.

- Pounding of adjacent structures.

  Provision of a seismic separation gap between adjacent structures, particularly in the case of newer construction, was common. However, in many instances the clearance was inadequate and impact occurred. The consequences of impact was especially severe when floors were at different heights, so that the floors of one structure struck the columns of its neighbour. One such example is shown in Fig. 12. In some instances it was the intent of the designer to provide a seismic gap. However, a lapse in quality control either during construction or subsequent to completion meant that the gap was not maintained. For example, several cases were observed where formwork had been left in place effectively nullifying the gap. Appropriate flashing of the gap adequately to prevent the accumulation of debris in the clearance during the working life of the facility had not been installed in other instances.

  One problem peculiar to Mexico City is large scale settlements which have, and still are, occurring in buildings located on the soft clay soils. The settlement is typically non-uniform over the extent of any one site with the result that very few structures still stand in their as-constructed vertical alignment. The relative tilt in adjacent structures had reduced the seismic gap for some buildings prior to the earthquake, thus increasing the potential for collision.

  Another failure mode related to the absence of effective seismic gaps was that caused by the propping action of lower height adjacent structures. The lower portion of the taller structure

Figure 5 Opening of 90° hooks to column ties.

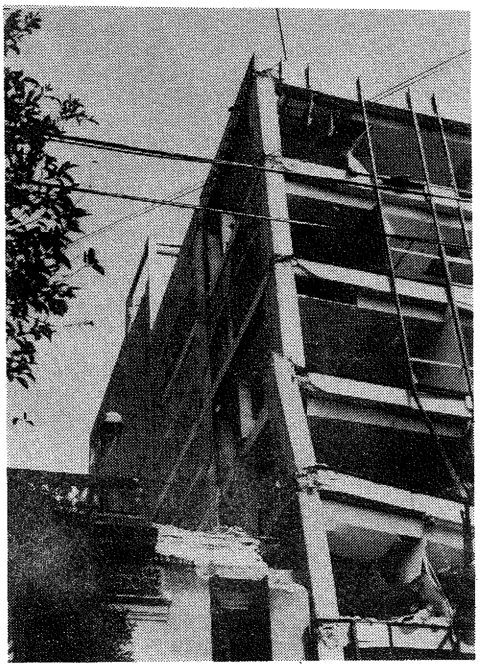

Figure 6 Building on Calle de Tanala which has suffered severe beam/column joint failures.

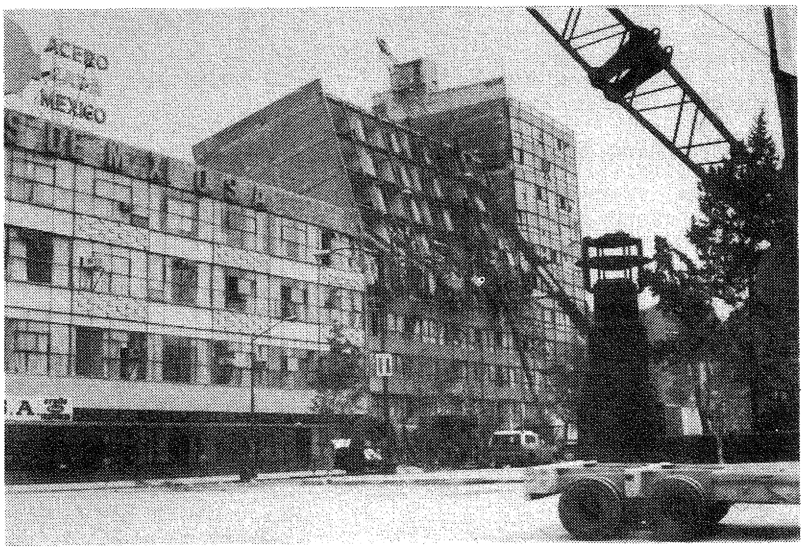

Figure 7 Collapse of the Hotel de Carlo due to Column failure at rear.

Figure 8 Upper storey collapse in the Continental Hotel.

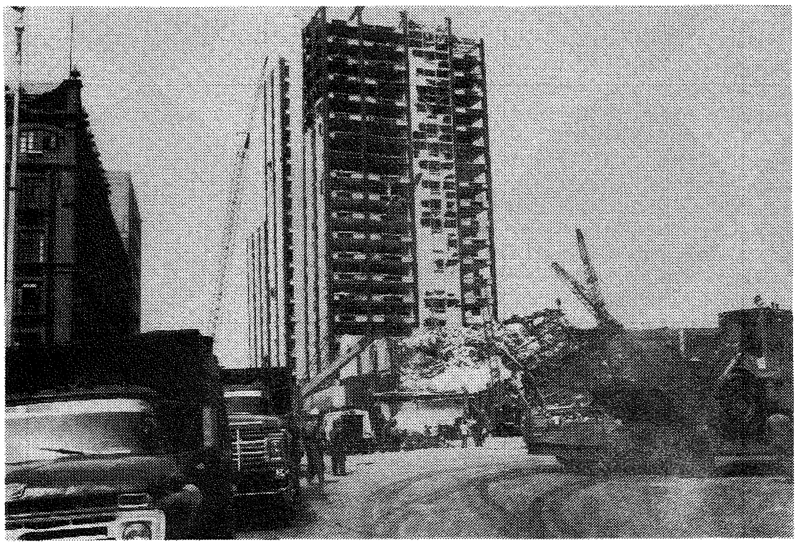

Figure 9 Pino Suarez Towers during clean-up operations. In foreground, debris from 20 storey tower which collapsed over adjacent 14 storey building.

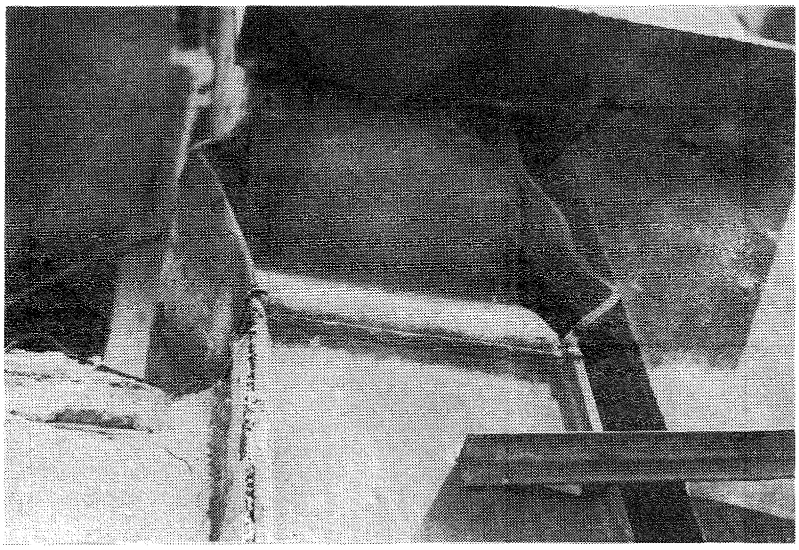

Figure 10 Local buckling in steel box columns—Pino Suarez Tower, still standing but with 1.2m lean.

was stiffened by the propping but the lower levels above prop height continued to respond with full flexibility. Failure generally occurred in these upper levels. Many of the older low rise masonry or adobe structures were built with no seismic gap. However, the characteristics of this earthquake were such that these short period structures were not strongly excited. Damage did occur to some of these low rise structures when a flexible frame structure impacted against them. The characteristics of failure of this type were diagonal tension cracking extending to an angle of approximately 45% from the point of impact across the facade of the lower structure to ground level. In one case, the cracking was observed uninterrupted through three adjacent buildings.

- Torsional eccentricities introduced by building configuration.

  Torsional eccentricity was responsible for the poor performance of some buildings. Given the population density of Mexico City, the temptation is to develop any plot of land regardless of its shape. Consequently it is not uncommon to see triangular (in plan) structures occupying the land bounded by two streets meeting at an acute angle. To suit a retail occupancy, the two street frontage faces would be open frame with glazing and the third back wall probably a shear-wall formed by a concrete frame with brick infill. The result of this configuration is a large eccentricity between the centre of stiffness and the centre of mass. Several structures were severely damaged or collapsed because of the high ductility demand on the columns remote from the main boundary walls (these columns typically had only nominal ties with right angle hooks). A notable exception was the steel framed National Lottery Building which was undamaged externally despite its triangular plan form and glass curtain wall on two faces.

- Weak column-strong beam frames.

  Numerous instances of column failure in shear, torsion or flexure resulting in the partial collapse or collapse of buildings were observed. Many of these failures were caused by the use of deep spandrel beams or unseparated infill panels which had the effect of shortening columns and increasing shear forces. The detailing of the columns could not match the requirement for ductile behaviour.

- Weak flat slab-column junctions.

  Several failures due to inadequate shear capacity in flat slabs adjacent to columns were observed. The waffle slab in various forms is a common slab type used in Mexico City. A typical failure in a partially collapsed building is shown in Fig. 13. Fig. 14 shows an example of a collapse of an eleven storey flat slab structure. The columns remain standing, but separated from the slabs they once supported by shear failures in the junction between slab and column.

- Additional loading.

  Some structures, due to a change in occupancy, were carrying imposed loads in excess of those assumed in design. This may have contributed to collapse or damage.

- Poor steel-to-concrete bond.

  The team was surprised to see numerous instances where concrete had debonded completely from the reinforcing steel especially in regions where "hinging" had occurred and also the ease at which some structures were being demolished by hand with sledge hammers. One case was reported of a full beam cage being recovered intact and in another, reinforcing bars were being removed apparently undamaged from a slab under demolition. No obvious reason for this behaviour was established and further investigation is clearly needed.

6.3 Damage to Buildings in the Epicentral Region Including: Cd Guzman, Chilpancingo, Acapulco, Ixtapa, Lazaro Cardenas and Playa Azul

Cd Guzman was one of the few cities in which adobe construction was severely damaged. It has been estimated that approximately 40% of the buildings in the city were of adobe type construction and of these some 75% were damaged to some extent. Damage was generally to the front rooms of houses which opened directly on to the street. Several villages around Guzman were also severely hit, but it was interesting to note that in many others, structures of similar construction survived almost completely undamaged.

Chilpancingo, which had been severely hit in previous earthquakes, was also affected by these earthquakes. Cracking was observed to the church tower in the square. There was also some damage to the Departmental Buildings around the Main Square. This damage was generally non-structural or to elements which had not been adequately separated.

It was reported that there was no damage in Acapulco.

At Ixtapa, a tourist resort, none of the nine or so high rise hotels escaped damage in some form or other and many had been closed. The Sheraton, a 14 storey structure suffered damage between the main building and an attached atrium structure even though some attempt had been made by the designers to allow each structure to act independently. Some suffered extensive structural and non-structural damage while a few including the Dorado Pacifico suffered considerable non-structural damage.

Damage to buildings at Lazaro Cardenas (approximately 30 km south of the epicentre) was reported to be mainly to structures of two or more storeys. Several structures including schools collapsed.

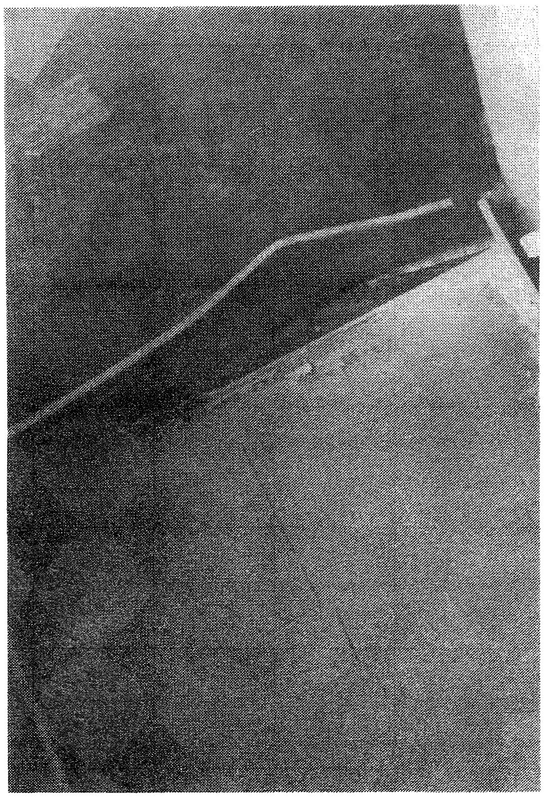

Figure 11 Lack of fusion in fillet weld to a diaphragm plate in the steel box columns—Pino Suarez Tower, collapsed 20 storeys.

Figure 12 An example of pounding between neighbouring structures with floors at different elevations.

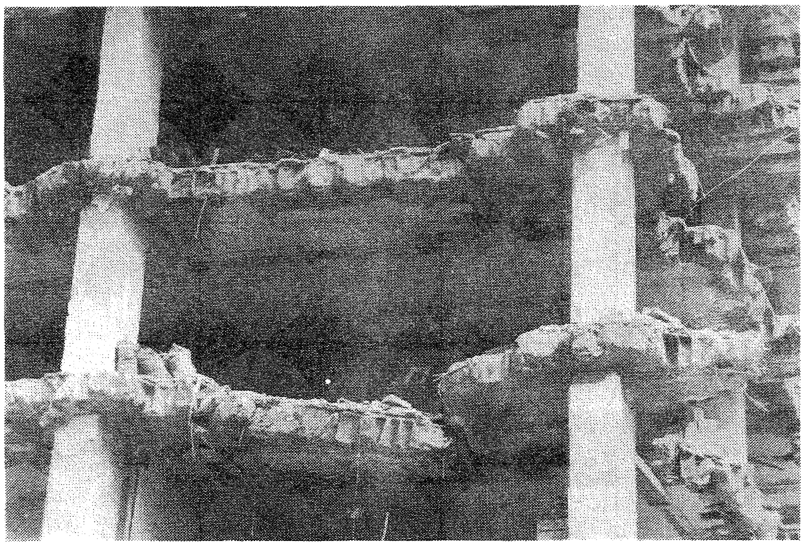

Figure 13 Flat slab-column joint failures, Public Water Supply building.

A number of hotels were badly damaged in Playa Azul, a resort area to the north of Lazaro Cardenas. In one hotel three separate, three storey, wings of a four wing complex partially collapsed due to column failures. The failures were due in the main to the existence of a soft first storey caused by infill walls being present only in the upper floors. The lack of damage to single storey, adobe construction so close to the epicentre was of particular interest.

7. NON-STRUCTURAL DAMAGE TO BUILDINGS IN MEXICO CITY INCLUDING BUILDING SERVICES

General

This section summarises the behaviour of non-structural elements and of building services.

Two general comments can be made:

(a) Very few specific steps had been taken to limit damage to secondary elements by way of designed separation from the structure, or independent bracing.

(b) The value of New Zealand requirements for separation was demonstrated in many examples where brittle secondary elements had not been separated and had suffered severe damage.

Ceilings

The range of ceiling types was similar to the range in New Zealand, but there were apparently few timber framed ceilings.

The most common suspended ceiling consisted of a lightweight metal grid with lightweight ceiling panels of rock-fibre or similar material. The wire hung rail system was sometimes exposed and sometimes concealed, but there were no examples of the use of effective bracing. As a rule, light fittings were independently wire hung to finish flush with the suspended ceiling.

Heavier ceilings were also used, examples being insitu plaster on mesh, plasterboard sheets and fibrous plaster tiles.

Ceilings had been damaged in several ways:

- By collapse of the adjoining or supporting structure.
- By damage to panels and/or rails that had been restrained by the adjacent elements.
- By panels falling out, although damage to the rail system was slight. This was common. (Fig. 15).

Partitions

Single skin brick partitions are most common, especially in older buildings. The brickwork is plastered with an applied decorative finish of paint or tiles. Stone facings are used over brick partitions in feature areas such as foyers.

Damage to these partitions was frequent, arising from lack of separation. Damage took the form of crushing of brickwork at junctions with the structure, diagonal shear cracks and cracking at weak sections, such as around doors and other openings. In more severe cases, brick panels had collapsed, but even where damage to the brickwork appeared slight, finishes of plaster, tiles or stone had spalled off.

Demountable partitions are also used. These generally survived undamaged, except when there were structural failures.

Timber framed partitions are uncommon.

Stairs

Insitu concrete stairs are usual, but steel is also found. There was usually no positive separation at floor landings and damage had occurred in many cases as a result of this (Fig. 16). Even where structural damage to stairs was slight, architectural finishes were damaged where movement had occurred between the stairs and adjacent elements.

Windows and Glazing

Damage to windows systems, and particularly to glazing, was widespread in the severe damage zone (Fig. 17) but there were also many anomalous situations in which glazed curtain walls were undamaged or only slightly damaged, despite apparent deficiencies in the structural form of the building.

Some observations were:

- Seismic sub-frames for windows are not used.
- In many cases of both curtain wall systems and conventional windows, the tolerance in the rebate between sheets of glass and window frames had evidently been sufficient to accept interstorey drift.
- Glazed sashes were sometimes less damaged than fixed glazing.
- Steel strap connectors between curtain wall framing and the structure probably admitted some movement.
- Glass breakage was high in building facades which alternated glazing with stiffer spandrel panels.
- Two examples of fin reinforced glazing were both damaged.
- No examples were seen of silicone rubber 'stuck on' glazing.

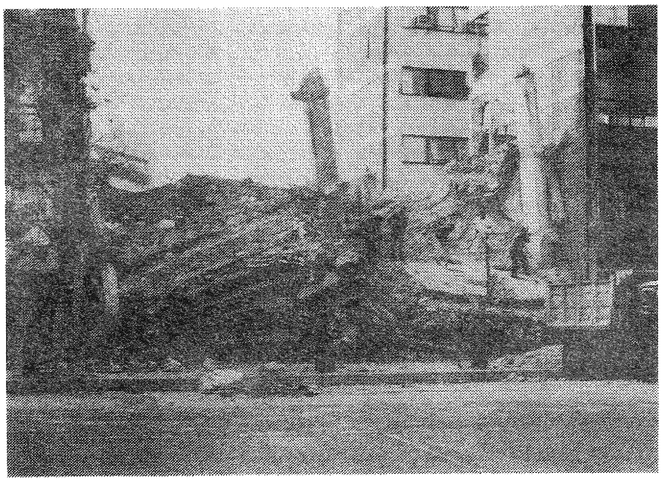

Figure 14 Flat slab failure in an eleven storey structure on Av. Oaxaca.

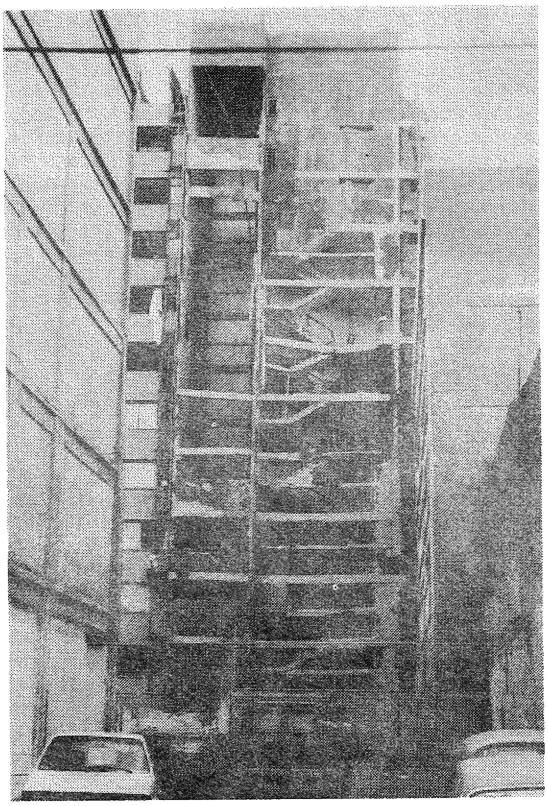

Figure 16 Damage to stair tower and hinging in strings due to non-separation.

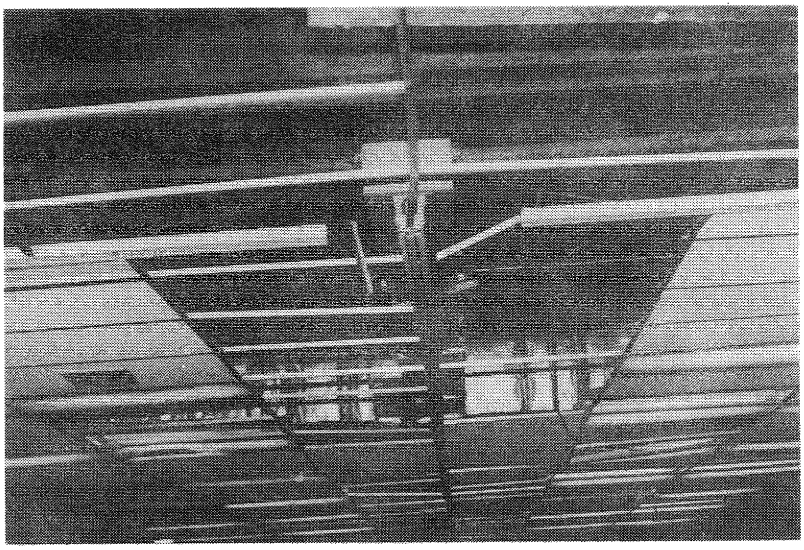

Figure 15 Damage to suspended ceiling system.

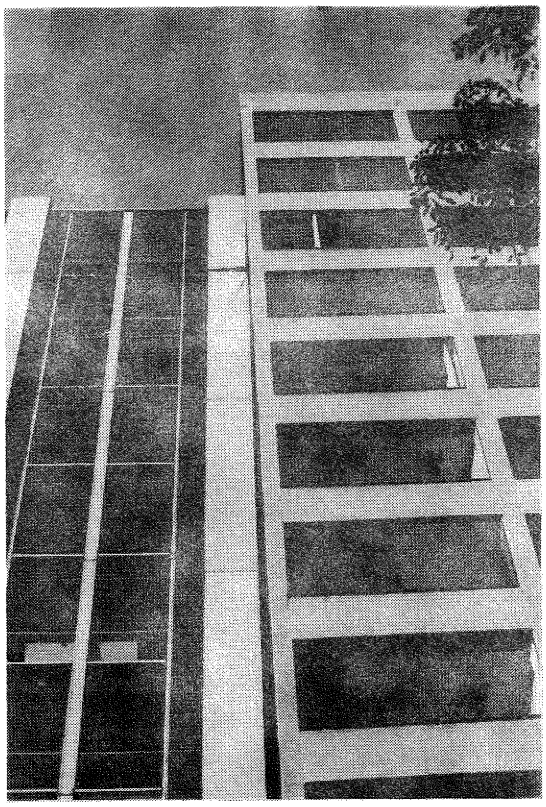

Figure 17 Damaged glazing system.

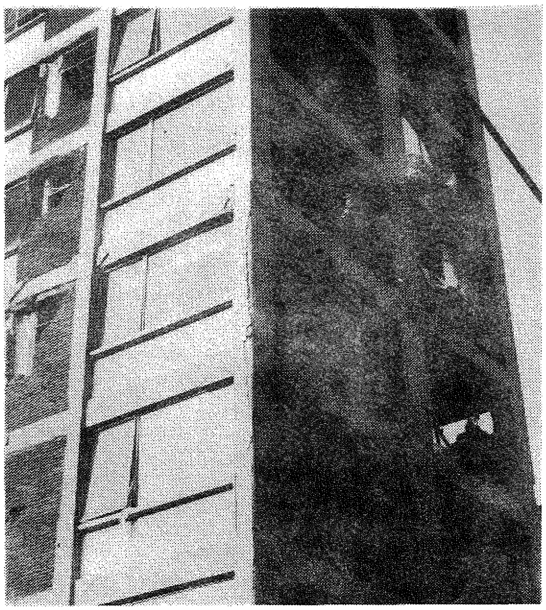

Figure 18 Damaged brick infill panels.

Figure 19 Telecommunications tower, Mexico City.

Exterior Cladding

Apart from glazing, the dominant cladding was plastered brickwork, used as infill panels without any separation (Fig. 18).

Other cladding examples were:

- Stone slab and tile facings applied to brick or insitu concrete. Slabs were broken or detached where movement had occurred.
- Brittle insitu plaster on mesh panels in a steel framed structure. No separation was provided and damage was extensive.
- Lightly reinforced insitu and precast concrete elements, unseparated from the structural frame. One building containing such elements was severely damaged.
- Thin sheet metal cladding, in strip form, lightly attached to brick infill panels. Large areas of cladding were detached although brick walls appeared undamaged.

Building Services

Surprisingly few examples of failure of building services were reported or observed. There was negligible evidence of seismic restraint of items of building plant, pipework or ducting. Air handling and electrical equipment appeared to have been unaffected by the earthquake even though plant items were sometimes not bolted down. A large vertically mounted oxygen storage tank in the Central Medical Centre was undamaged although the building enclosure was shattered. The absence of significant damage probably results from the predominant long period characteristics of the earthquake.

Lifts had remained operable in some buildings even where there was obvious damage to the lift shaft enclosure, but apparently not to the guide rails.

Mexico City does not have a reticulated gas system; instead tankers supply gas to storage tanks commonly seen on building roofs. On the roof of one office building an unfixed gas tank had rolled over but no other damage to gas systems was seen.

8. DAMAGE TO CIVIL ENGINEERING STRUCTURES

8.1 Mexico City

In general, civil engineering structures performed well in the earthquake. There were no reports of damage to steel towers, underpasses and retaining walls while only one bridge was slightly damaged. The bridge was made serviceable within a day or so of the earthquake. However, surface settlement of up to 300 mm did occur in the fills behind some retaining walls.

The reinforced concrete telecommunications tower at the central telephone exchange suffered some damage to upper coupling beams (Fig. 19) and to the covered walkways to adjacent buildings. The tower appears to be plumb and is still in use. It is not known whether the microwave antennae were damaged or needed to be realigned.

Two 40 m tall reinforced concrete multi-cell grain silos, full of grain at the time of the earthquake, were severely damaged or collapsed. The walls of the damaged silos failed in compression and yielded in tension just above the hopper cones. They had a permanent deformation of about one metre. The other silo installation collapsed completely also above the hopper cone after pounding by an adjacent stiff grain cleaning house. There was a separation between the structures but they were connected together by a roof slab at the top. It was reported that the silos were designed to ACI 318 with accelerations of 0.08g.

8.2 Epicentral Region

The most widespread earthquake damage was the settlement of the approach fills at bridge abutments. Some two weeks after the earthquake this had been repaired by the use of plant-mix. Apart from this, there was little sign of movement or damage to bridges in the region. Two notable exceptions were a bridge on Highway 200 near Tecpan and twin bridges over the Rio Balsas servicing the port of Lazaro Cardenas.

The bridge near Tecpan is reinforced concrete with five spans and is on a 24 degree skew. The spans are simply supported on elastomeric bearings and restrained laterally by reinforced concrete shear keys. The spans are not tied together. Under the action of longitudinal forces the spans moved in the direction of the skew and shattered the shear keys. The movement as indicated by the centre line marking, was about 100 mm whereas the offset at the kerb was 200 mm. Obviously some movement had occurred in a previous earthquake.

The twin bridges on the Rio Balsas are reinforced concrete, with single stem piers and with 5 prestressed concrete simply supported spans. A number of the piers suffered major damage due to hinging and loss of confinement (Fig. 20). The bridge showed evidence of longitudinal movement, and damage to the lugs restraining the spans transversely. In addition, the approach fills had settled and suffered tension cracking longitudinally. The damage was sufficient to close one bridge to vehicles while only one unladen vehicle per time was permitted on the other.

The almost completed grain handling and storage facilities at the Port of Lazaro Cardenas were severely damaged. At the time of the earthquake the silos did not contain grain, however shear cracks were evident in the walls of one of the silos. The five storey structure above

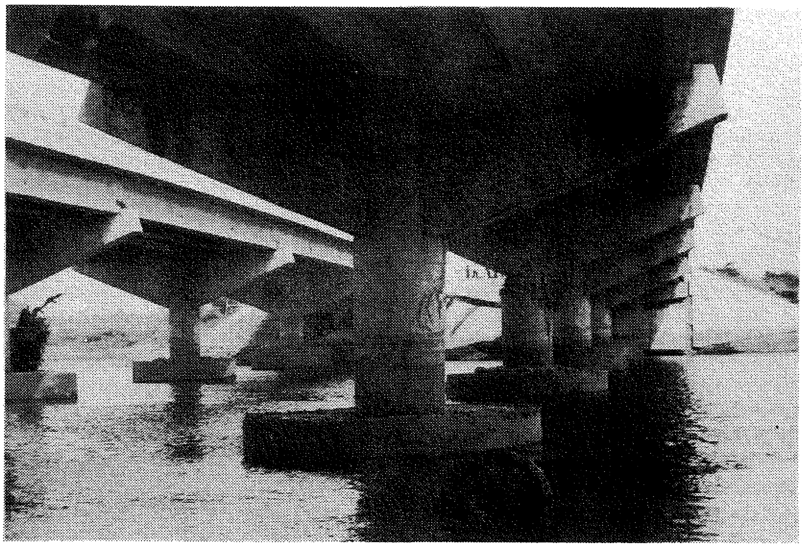

Figure 20 Bridge pier damage.

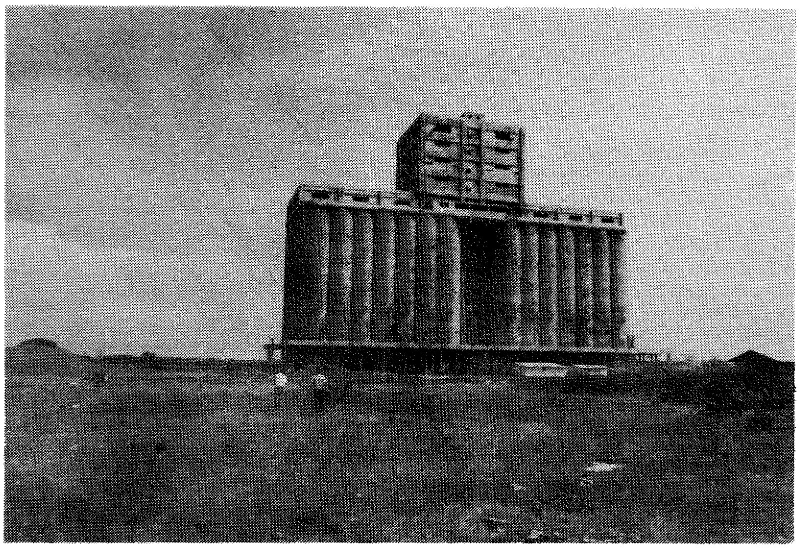

Figure 21 The structure on the grain silo has lost its lowest storey.

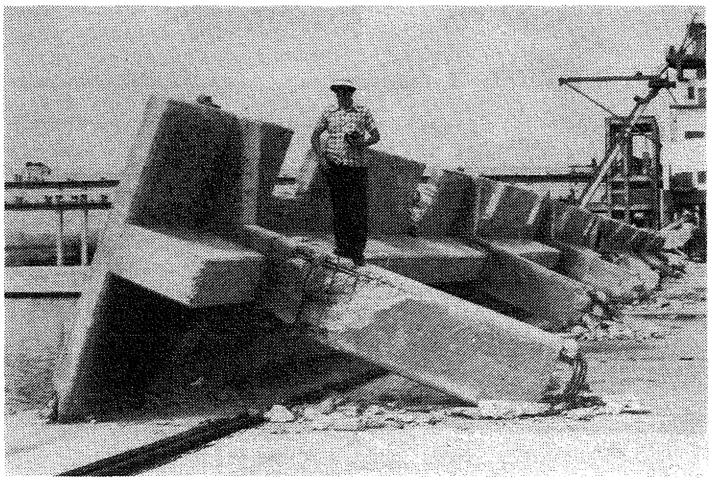

Figure 22 Collapse of conveyor support structure.

the silos partially collapsed and lost a complete storey due to column shear failure (Fig. 21). In addition, the reinforced concrete conveyor support structure to the grain unloading facility on the adjacent wharf collapsed. Collapse appeared to start at the free end (Fig. 22) due to inadequate anchorage of the column bars into the wharf deck. The twisting caused torsion cracking of the spine beam and failures of the beam at cut outs in the slab. Failures of the cantilever columns in some cases involved complete disintegration due to inadequate column ties and the use of 90° hooks. The large structural steel mobile grain elevator on the wharf was restrained by angles welded to the rail but was undamaged.

At the container terminal the container storage pavement slabs settled 200-250 mm relative to the piled wharf structure due to liquefaction. The construction joints in the concrete pavement opened and three large sand boils formed, one about 10 m across with some gravels up to 40 mm diameter mixed with the sand.

There are two hydro-electric stations on the Rio Balsas each with rock fill dams. At La Villita where accelerations of 0.45g were recorded on the crest of the dam, longitudinal tension cracks up to 25 mm occurred.

Similar cracking occurred in previous earthquakes and is due to differential settlement as the core is founded on bedrock and the shoulders of the dam on gravels. Further up the river some minor cracking occurred on the crest of the Infiernilla Dam. At the time of the earthquake the crest was being raised and the accelerograph was resited on an intermediate level berm. Peak ground accelerations of 0.34g were recorded.

No damage was reported either in the underground power station nor in the yards, but two of the six generators tripped out. These were quickly put back on line.

9. DAMAGE TO STORAGE RACKS

Extensive failure of storage racks occurred in the stores and spare parts warehouse of the Sicartsa Steel Mill in Lazaro Cardenas. The warehouse consists of a three bay portal frame with concrete columns and steel rafters and is serviced by overhead travelling cranes. The area enclosed is about 100 m x 150 m.

A wide range of spares and stores required for the operation of the steel mill are held, ranging from clothing through to large electric motors. In all, some 75,000 different classes of units are held with the total number of items being several millions. The effect of the collapse of some 60% of the storage racks was to mix many of these items together. The resulting mess of twisted racking and stored items is shown in Fig. 23.

In addition there was damage at the knee joint junction of the steel rafters and concrete columns. Also, the OHT cranes could not be operated due to severe damage to the corbels supporting the crane runway girders. The warehouse offices containing records and computer stores control facilities were wrecked (Fig. 24).

The effects of the damage was devastating to the morale of the stores staff involved and represented the most serious damage suffered by the Sicartsa Steel Mill as a result of the earthquake.

10. DAMAGE TO LIFELINES

Highways and Streets

There was no significant damage to highways either in Mexico City or the epicentral area. Several rock slides occurred during the earthquake and there were more two or three weeks later (Fig. 25).

Tension cracking and compression buckling of streets and pavements was evident in Mexico City but was of a relatively minor nature (Fig. 26).

Electrical Generation and Transmission

No damage was reported to electrical generation plant and equipment in thermal power stations close to Mexico City nor to the hydro-electric stations close to the epicentre.

Several transmission towers close to the sea at Lazaro Cardenas were reported damaged from the effects of the tsunami.

Airport

The international airport at Mexico City was closed for less than half an hour following the earthquake while inspections of the runways and facilities were carried out. Damage was reported to buildings, an underground fuel line was ruptured and some tension cracking occurred in aprons and in a taxiway between runways. The 3,600 m long asphalt runways were undamaged.

Communications proved to be the biggest operational constraint due to failure of the links through the microwave tower at the Ministry of Communications and Transport (SCI Centre). As a result, it was only possible to communicate with aircraft for 15 minutes prior to arrival.

Water Supply

Breaks in water mains occurred mainly in the soft soils in areas of Mexico City to the South and East. Also, the distribution network was affected by fractures occurring due to the collapse of buildings.

Some three weeks after the earthquake, almost 5 million people, as well as the airport, were reported to be without

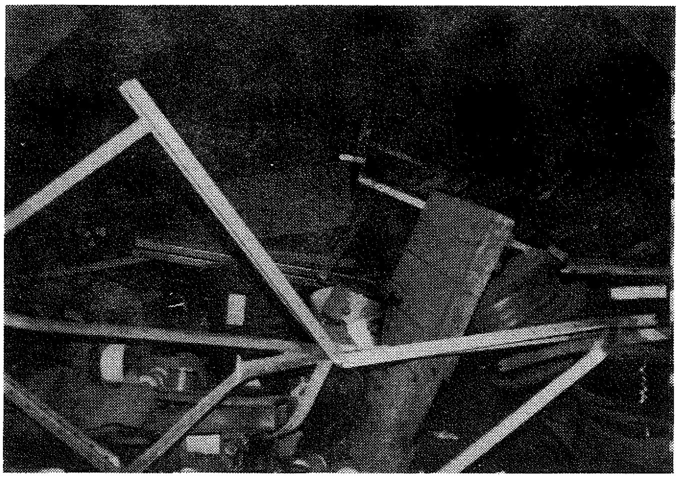

Figure 23 Collapsed storage rack.

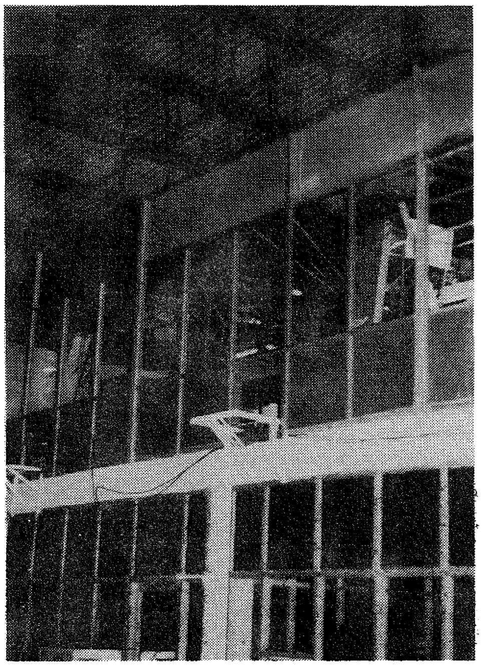

Figure 24 Damaged warehouse offices.

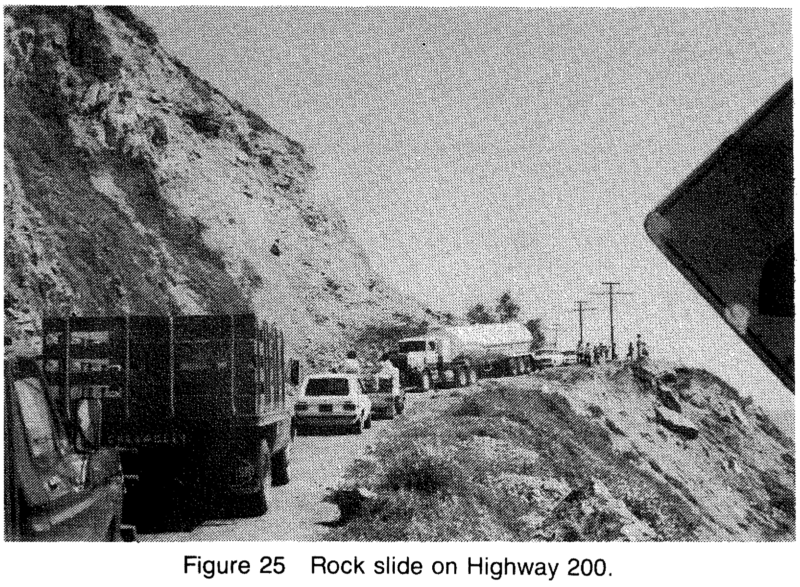

Figure 25 Rock slide on Highway 200.

mains water and had to be supplied with potable and non-potable water by tanker trucks.

Gas Supply

In Mexico City gas is delivered to storage tanks in buildings and apartments by tanker truck. Consequently, there is no underground gas distribution system and there were no fires fed by gas from leaking or ruptured gas mains. The only serious fire reported was due to a leak in the gas storage tank in the St. Regin Hotel. This fire spread to an adjacent department store and an office building occupied by a government department.

Telecommunications

Apart from buildings in Mexico City, the telecommunication system suffered the most severe damage.

Much of the damage resulted from the overturning of cabinets containing switching equipment (Fig. 27). Also, as a result of severe damage or partial collapse of two buildings housing exchanges for international calls, all operator assisted services were eliminated. The partial collapse occurred at the Victoria exchange where 14 operators and staff were rescued and 10 were killed.

Emergency lines to exchanges in other Mexican cities enabled some international traffic to be handled.

In addition, two mobile digital exchanges were supplied by the US. By this means and the use of new equipment in store at the time and awaiting installation, it was possible to handle 25% of the long distance traffic some two weeks after the earthquake.

CONCLUSIONS

1. The characteristics of the earthquake, especially its dominant period, were such that buildings were attacked selectively and damage was of a special nature.
2. Many buildings suffered damage in storeys about mid-height, for example, from the fourth to the eighth floor in a twelve storey building. The reason for this is not clear. Possibly soil-structure interaction contributed. More study is needed.
3. In Mexico City, buildings which collapsed or which were severely damaged included some buildings designed to comply with the 1977 Code as well as with earlier codes.
4. Mexico City Codes have hitherto offered little encouragement to designers to detail for ductile behaviour. It will be interesting to see whether the October 1985 emergency provisions offer enough margin between loads prescribed for non-ductile and for ductile structures to persuade designers to detail for ductility.
5. The use of structural steel will not in itself overcome problems of inadquate design and workmanship errors, and so ensure good seismic performance.
6. Almost universally beam and column ties in reinforced concrete structures had right angle hooks where there should have been proper anchorage. Ineffective ties contributed to many failures.
7. Pounding of adjacent structures even though seismic separation gaps were usually provided, was a significant contribution to damage.
8. The recorded maximum ground acceleration corresponds roughly to the 500 year return period ground acceleration for soft soils in Mexico City.
9. Even in the epicentral zone where the strong motions records show that there was vigorous high frequency as well as low frequency content, there was selective attack of larger structures. One and two storey adobe and brick houses were largely unscathed, except in a very few towns.

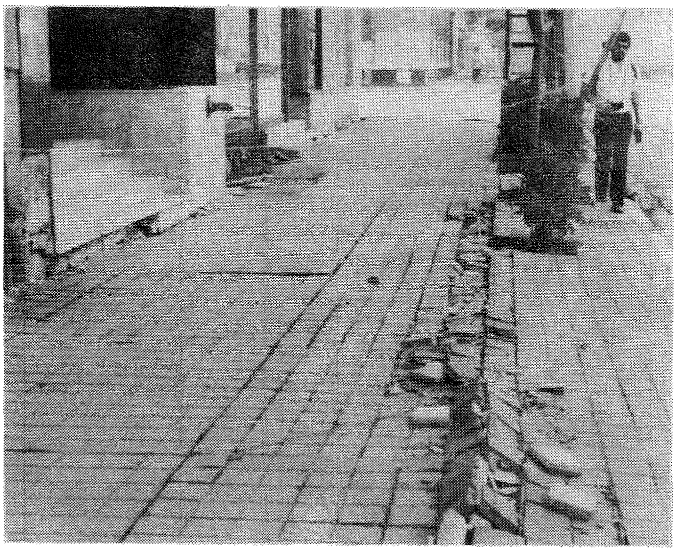

Figure 26 Compression buckling of pavement.

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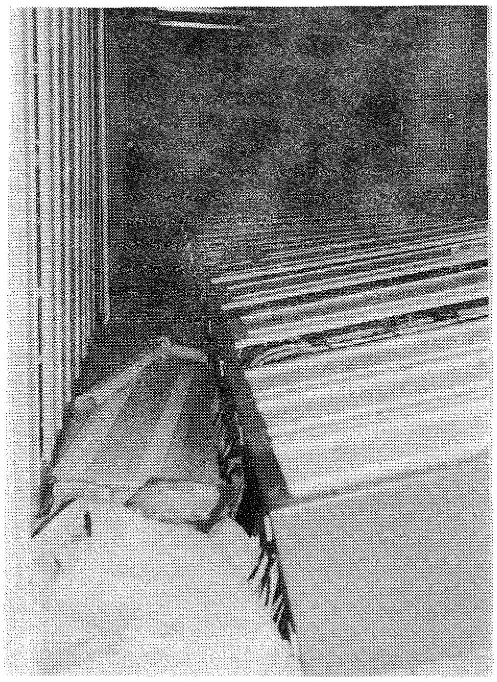

Figure 27 Overturned switch cabinets.