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THE SEPTEMBER 19TH, 2017 PUEBLA, MEXICO EARTHQUAKE: FINAL REPORT OF THE NEW ZEALAND RECONNAISSANCE TEAM

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ABSTRACT

This report presents the observations and findings following the 2017 Puebla earthquake that occurred in Mexico on September 19th, 2017. The reconnaissance mission was a collaboration between the New Zealand Society of Earthquake Engineering (NZSEE), the Universidad Autónoma Metropolitana (UAM) Azcapotzalco, the American Concrete Institute (ACI) Disaster Reconnaissance team, and the Colegio de Ingenieros Civiles de Mexico (CICM). During the earthquake, 77 buildings suffered partial or total collapse and more than 8,000 buildings experienced damage ranging from slight damage to significant structural damage necessitating demolition. As observed in previous earthquakes, the unique soil conditions of Mexico City resulted in extensive damage to the city's infrastructure, primarily due to local site effects. The earthquake caused relatively more damage to buildings built on transition and soft soil zones (i.e. between hard and deep soft soils) than those on hard soils.

The NZSEE and UAM team focussed on areas with widespread and extensive damage. They also assessed the performance of repaired and retrofitted buildings after the 1985 Michoacán earthquake. It was found that the lessons learnt from the 1985 Michoacán earthquake led to some risk mitigation measures which benefited several buildings in the 2017 earthquake. Retrofitted buildings were found to have performed very well with little or no damage when compared to other buildings.

INTRODUCTION

On Tuesday, September 19th, 2017, at 13:14 pm local time (18:14 UTC) a magnitude M_W 7.1 earthquake struck the central part of Mexico [1]. The epicentre was located 12 km south-east of Axochiapan, Morelos, approximately 120 km away from downtown Mexico City [2]. The affected areas were localised in the metropolitan area of Mexico City (21.2 million people), Puebla (1.6 million people), and Morelos (2 million people). The death toll was 369, out of which 228 were in Mexico City [3]. In the urban area, 77 buildings partially or totally collapsed, and 8,000 buildings experienced different levels of damage ranging from severe structural damage requiring demolition to damage to infill wall only [4].

This report summarises the key findings of the New Zealand (NZ) reconnaissance team, which in October 2017 spent about a week in Mexico City assessing the extent of damage to buildings. The team focused on areas where local site effects could have contributed to more pronounced damage in buildings. The team also assessed the performance of repaired and retrofitted buildings, which for most were retrofitted following the 1985 Michoacán earthquake. Where feasible the performance of structural elements and damage to non-structural building components were also assessed.

SEISMIC SETTING OF MEXICO

Seismological Features of Mexico

Mexico is located at the border of three major tectonic plates, the North American, the Cocos and the Caribbean plates (Figure 1). Two other plates, i.e. the Rivera microplate and the Pacific Plate, lie west of the Cocos Plate. The collision between the Pacific and the Cocos plates has produced the Jalisco block [5]. Due to the higher density of the oceanic plate compared to the continental crust, the Rivera Plate and the Cocos Plate subduct beneath the North American Plate. However, the rate of movement of the Rivera Plate and Cocos Plate is not the same. While the Rivera Plate moves northwest at about 20 mm per year, the Cocos Plate moves at an average rate of 70 mm per year. The North American Plate moves westward, and the Cocos Plate moves north-eastward. The subduction of the Cocos Plate under the North American Plate leads to the creation of a fault along the south-west coast of Mexico: the Middle America Trench (MAT) [6].

History of Mexican Earthquakes

Mexico has a long seismic activity history with the first reported earthquake in 1568 near the northeastern corner of the Jalisco block [7]. Most of the historical earthquakes have occurred in the southern part of Mexico along the subduction zone. Mexico has also experienced several intraplate earthquakes (Figure 1).

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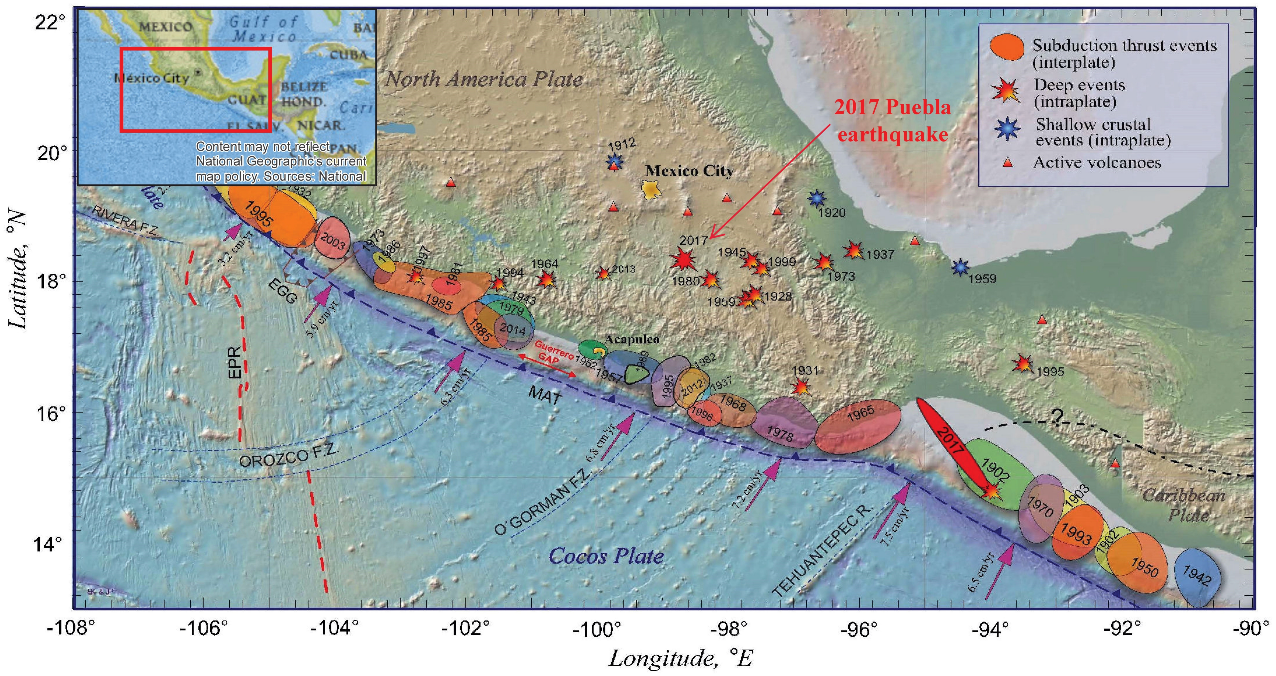


Figure 1: Localisation of seismic events (interplate and intraplate) in Mexico [8].

Nevertheless, it is only in the 19th century with the development of measurement instruments that scientists could record earthquake events [9]. The 20th century saw the evolution of seismic recording stations enabling more accurate recording of earthquake shaking. The three major earthquake events of the 20th Century in Mexico are: the 1932 Jalisco earthquake (M 8.1), the 1985 Michoacán earthquake (M_W 8.0), and the 1995 Manzanillo earthquake (M_W 8.0). The largest intraplate earthquake prior to the 2017 Puebla earthquake was recorded on December 11th, 2011 [10].

Soil Conditions and Seismic Zonation of Mexico City

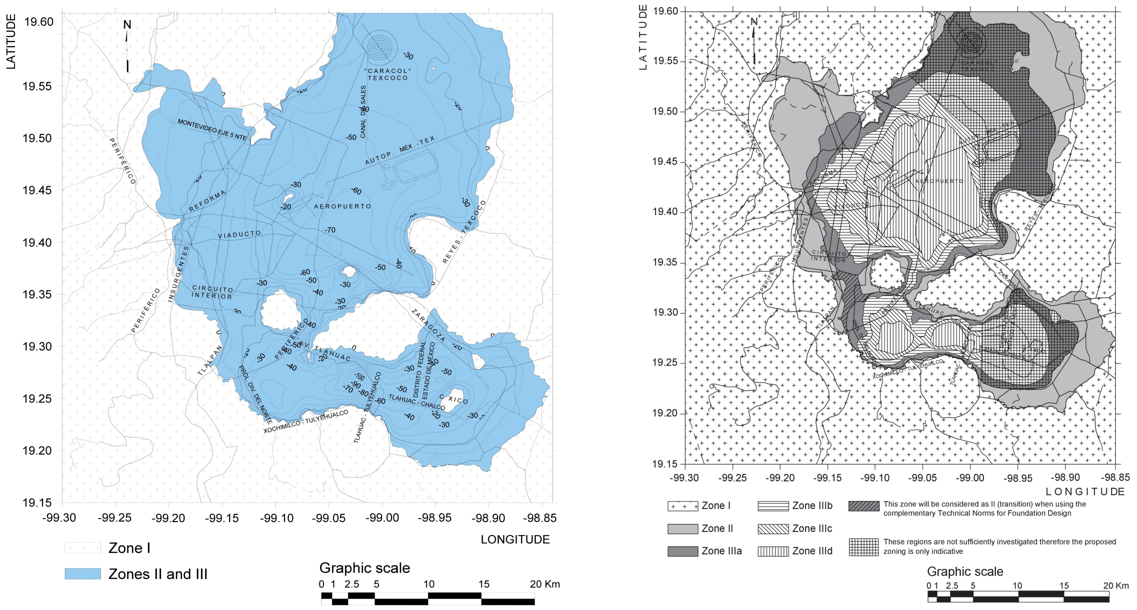
The soil conditions in Mexico City are unique. The capital, founded in 1325, was located on two islands in the middle of the Lake Texcoco [11]. The region had five lakes, and several marshes surrounded the ancient town [12]. As the city expanded, land was reclaimed on the previous lake areas which led to different soil conditions under the urban area of Mexico City [13]. Figure 2a shows the thickness of the soft soil layers in Mexico City.

Local site effects in Mexico City started to be thoroughly studied in 1959 [14]. Nevertheless, the 1957 emergency regulations [15] already considered a seismic shear coefficient used for design. Three soil types, firm, transition and soft soil, were taken into account [16]. In the 1966 Mexico City building code [17] the transition and soft soils were, however, considered in the same category [18]. Ten years later, the three soil categories were defined based on the soft soil depth: firm soil for deposit of 3 m or less, transition soil for a thickness between 3 and 20 m and soft soil for 20 m thickness and more [18, 19]. Recent version of the code took the thickness of the soft soil layer deposits (Figure 2a) into account to refine the seismic zonation for soft soils. The 2004 seismic code [20] considers six different seismic zones for Mexico City: I, II, III a, III b, III c, III d. Figure 2b shows the seismic zonation. Zone I, firm soil; Zone II, transition zone; and Zone III, soft soil. Zone III is further divided into four sub-categories, from a to d, and each of these sub-categories is assigned a different design spectrum, as shown on Figure 3.

Evolution of the Seismic Building Code in Mexico City

Mexico has a unique system of managing the seismic codes at the state and municipality levels. A common national code does not exist (although since 1969 there is a seismic guideline issued by the Federal Commission of Electricity at a national scale, which controls the construction of civil works [23]). In 2008, Mexico had 104 building codes (32 at state level and 72 at municipal level) [16]. However, over the years, the Mexico City Building Code (MCBC) acquired greater relevance in Mexico due to the size and population of Mexico City.

The first building code for Mexico City was published in 1921 [24]. It was based on allowable-stress design and only comprised spare information limited to material stresses and minimum dimensions [16]. It was followed by the 1942 MCBC [25] which saw the first inclusion of seismic forces in the Mexico City building code [18]. The 1957 emergency regulations [15] were issued following the 1957 Guerrero earthquake. They introduced higher seismic coefficients related on three type of soil (firm, transition, and soft) [18]. The 1966 MCBC version [17] merged the transition into the soft soil category [18]. It was only with the 1976 update [19] that the MCBC evolved to include the limit-state design approach [16]. It was also the first time that the ductility of the structure was explicitly taken into account in the Mexico City building code [18]. Emergency regulations were issued following the 1985 Michoacán earthquake [26]. They introduced an increase in the seismic-elastic coefficients for the soft and transition zone as well as an increase in the ground acceleration [18]. The 1987 Mexico City building code [27] led to a revised soil zonation in Mexico City with stricter design and detailing requirement for the transition and soft soil zones. The 2004 version is a major revision of the 1987 building code with the addition of site specific design spectra, the consideration of the duration of actions (permanent, variable, or accidental), and new requirements for foundation design [20]. Following the 2017 Puebla earthquake, a new building code for Mexico City which had been in development for several years, was released in December 2017 [28]. The evolution of the Mexico City building code indicates that the code was revised after each major earthquake (i.e. 1957, 1985) by considering the lessons



(a) Contour map of deep deposits depth [21].

(b) Seismic zonation of Mexico City [20].

Figure 2: Depth of soft soil and geotechnical zoning in Mexico City.

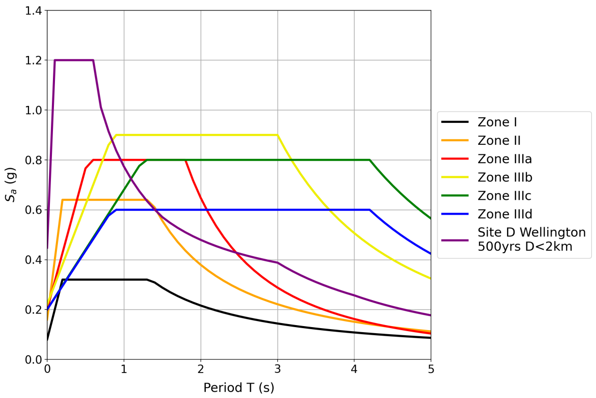


Figure 3: Elastic spectra for the six different seismic zones for Mexico City, 2004 code [20] compared with elastic spectra for Wellington [22] (Mexico City Elastic spectra = Design spectra × 2; where 2 is overstrength factor assumed by 2004 code).

learned from these earthquakes. All the learnings from the past earthquakes have led to the current structural design code in Mexico City.

1985 Michoacán Earthquake

On Thursday, September 19th 1985, a M_w 8.0 earthquake occurred on the Pacific coast of Mexico, in the region of Michoacán [29]. The 1985 Michoacán earthquake led to extensive damage in Mexico City with 757 buildings which suffered severe damage, partial or total collapse [18]. The death toll was estimated around 8,000 – 16,000 [30]. Intensities felt in the soft soil zones of Mexico City were much higher than in firm soil zone regions. On firm soil, i.e. in the hill zone, the maximum horizontal acceleration recorded was between 0.01 and 0.04 g. On the soft soil, however, the peak ground accelerations of up to 0.17 g were recorded [30]. Very high spectral acceleration amplitudes around 2 s were measured in soft soil zones and a long shaking duration included several damaging cycles at such sites.

In October 1985, a reconnaissance team from New Zealand travelled to the damaged areas. They assessed the extent of damage and gathered information on the unique characteristics of this earthquake. Readers interested in detailed findings following the 1985 reconnaissance mission are directed to the final report of the New Zealand team [30].

In 1985, the range of instrumentation to record ground shaking in Mexico was limited. As shown in Figure 4, in 1985, Mexico City had eleven recording stations. Four located in the firm soil zone (Ciudad Universitaria (CU01, CUIP and CUMV) and Tacubaya (TACY)), one in the transition zone (Viveros de Coyoacán (SXVI)), and six in the lakebed zone (Central de Abastos (CDAO and CDAF), Secretaría de Comunicaciones y Transportes (SCT1), Texcoco Sosa (TXSO), and Tláhuac (TLHB and TLHD)) [31]. The station SCT1 produced the highest recorded accelerations, and had since become famous in earthquake engineering as a textbook demonstration of the importance of site effects. Nevertheless, in some parts of the city, no actual measurement of the seismic intensity was available. To estimate the seismic intensity, engineers assessed the extent of building damage and correlated the degree of damage with the probable seismic intensities [32].

2017 Puebla Earthquake

On Tuesday, September 19th, 2017, on the 32nd anniversary of the 1985 Michoacán earthquake, at 13:14 local time (18:14 GMT) an intraslab earthquake (M_w 7.1) occurred approximately 127 km south-east of Mexico City. The rupture occurred inside the Cocos plate. The normal fault rupture within the Cocos plate occurred at an epicentral depth of 48.0 km [1].

Seismic demands in Mexico City depend mainly on soil conditions rather than being related of the size, depth, epicentral distance, and location of the source [3]. Figure 5 shows a map of Mexico City with response spectra for recording stations located in different zones (hill, transition zone, and soft soil), clearly indicating the influence of the site conditions.

The 2017 Puebla intraslab earthquake was smaller, closer to Mexico City and of a different type than the 1985 M_w 8.0 Michoacán interplate earthquake. Intraslab earthquakes, at close distances

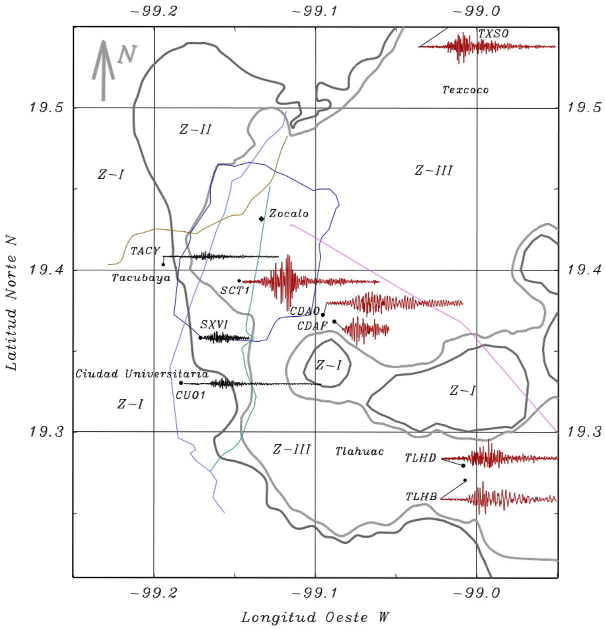


Figure 4: Map showing the location of the recording stations available in 1985 [31].

are likely to trigger different seismic features compared to earthquakes originating from the subduction zone. Singh et al. (2018) found that intraslab earthquakes can lead to higher PGA than interplate earthquakes with similar magnitude [3]. This is confirmed by a comparison of the ground motion records from the 1985 and 2017 earthquakes which indicates that interplate and intraslab earthquakes trigger different response in the Mexico City soil.

Figure 6a shows the 1985 and the 2017 spectral acceleration (Sa) values recorded at station CU (firm soil). The PGA value at CU was 0.06 g for the 2017 event compared to 0.03 g for the 1985 Michoacán earthquake. For period below T < 1.6 s the spectral Sa values were higher during the 2017 Puebla earthquake. Buildings with period T < 0.4 s were subjected to Sa values reaching up to 0.20 g Figure 6b shows the Sa values recorded at station SCT (soft soil). On soft soil, seismic demands during the 2017 earthquake were generally lower than in 1985. At SCT, the PGA was 0.11 g in 2017 but 0.17 g in 1985. On soft soil, for periods larger than T > 1.5 s, Sa values recorded during the Puebla earthquake were significantly smaller compared to the Michoacán earthquake. As it can be seen in Figure 6b, buildings of period T = 2 s located near the SCT station could have experienced Sa values above 0.92 g during the Michoacán earthquake, whereas during the Puebla earthquake, the peak Sa values reached around 0.61 g.

DAMAGE TO BUILDINGS

Damage Following the 2017 Puebla Earthquake

Distribution of Damage in the Mexico City Urban Area

De Anda Gil et al. (2019) surveyed 1,094 buildings in Mexico City [4]. They classified structural damage according to the European macroseismic scale (EMS-98) ranging from damage grade 1 (negligible to slight damage) to 5 (destruction) [33]. They reported 32 collapsed building (damage grade 5), 45 buildings with very heavy damage (damage grade 4), and 226 buildings with substantial to heavy damage (damage grade 3) [4]. Figure 7 shows a map of Mexico City with the buildings which suffered a damage grade 3 (in green), 4 (in red), and 5 (in black). The background overlay represents the geotechnical zones according to the building code [20]. Severe building damage occurred in the neighbourhoods of Roma and La Condesa, and in the southern sector of Mexico City such as the street La Morena or the district Tlalpan (e.g. school Colegio Madrid and the university Tec de Monterrey). The previous section on the seismological features of the 2017 Puebla earthquake highlighted that in Mexico City the ground motion was amplified in areas where the soft soil layer was shallower. Building assessments confim that building damage was concentrated in the transition zone and the soft soil zone III a (represented with hatches on Figure 7). Less damage occurred in the firm soil and in the deep soft soil zones III c and III d.

Figure 8 shows statistics for the 1,094 damaged buildings assessed by De Anda Gil et al. [4]. Based on Figure 8a, 28% of the building surveyed were at least substantially damaged; characteristics of these most heavily damaged buildings are presented in Figures 8b-e. Figure 8b shows the distribution of heavily damaged buildings by number of storeys, indicating that most of the damaged buildings had a height between 3 to 6 storeys. Figure 8c and Figure 8e give information on the material type and lateral load resisting system (LLRS). Reinforced concrete (RC) and masonry are the most common used materials, with infill flat slab and infilled frames being the most frequent structural system. Figure 8d shows that more than 30% of the heavily damaged buildings presented torsion eccentricities (mostly due to their location at the corner of a block). Some common types of building damage observed are summarized in the following sections.

Some heavily damaged buildings were demolished, but in most cases, the preferred solution for damaged buildings was repair and retrofit to get buildings operable as soon as possible. As the insurance penetration in Mexico is low [35], no waiting time was needed to set up a claim. Thus, in October 2017, only one month after the earthquake, many repairs were already well underway. Considering the extent of damage, it appeared that Mexico has a good capacity in terms of construction workers and building materials to be able to respond to events such as the 2017 Puebla earthquake immediately after the disaster.

Concrete Column Failures

This earthquake exposed the well-known seismic vulnerabilities of existing RC building stock. Older buildings constructed before the 1985 Mexico earthquake generally performed poorly, and many of these buildings suffered column damage/failure. Common column failures observed included: lap-splice failure (splitting at the zone of the lap-splicing), crushing of unconfined concrete, shear failure due to short- or captive column effect, formation of plastic hinges in columns instead of beams. Examples of this damage are described briefly below.

Figure 9a and Figure 9b show examples of column shear failure observed in residential buildings. Figure 9c shows an example of insufficient confinement (and anti-buckling) stirrups which led to buckling of reinforcement bars. Figure 9d shows a column where damage was triggered by the interaction with a partial height infill. Figure 9e shows splitting cracks in the lap splice zone, which led to concrete debonding and the exposure of the longitudinal reinforcement.

Figure 9f shows concrete spalling, followed by bar buckling at the top of a column. The buckling of the longitudinal rebar at the top of the column in this picture appears to be a secondary outcome of shear-axial failure caused by the combination of high compression and shear demand in a deteriorated plastic hinge zone. Figure 9g shows the typical case of a short column failure caused by a partial height infill wall.

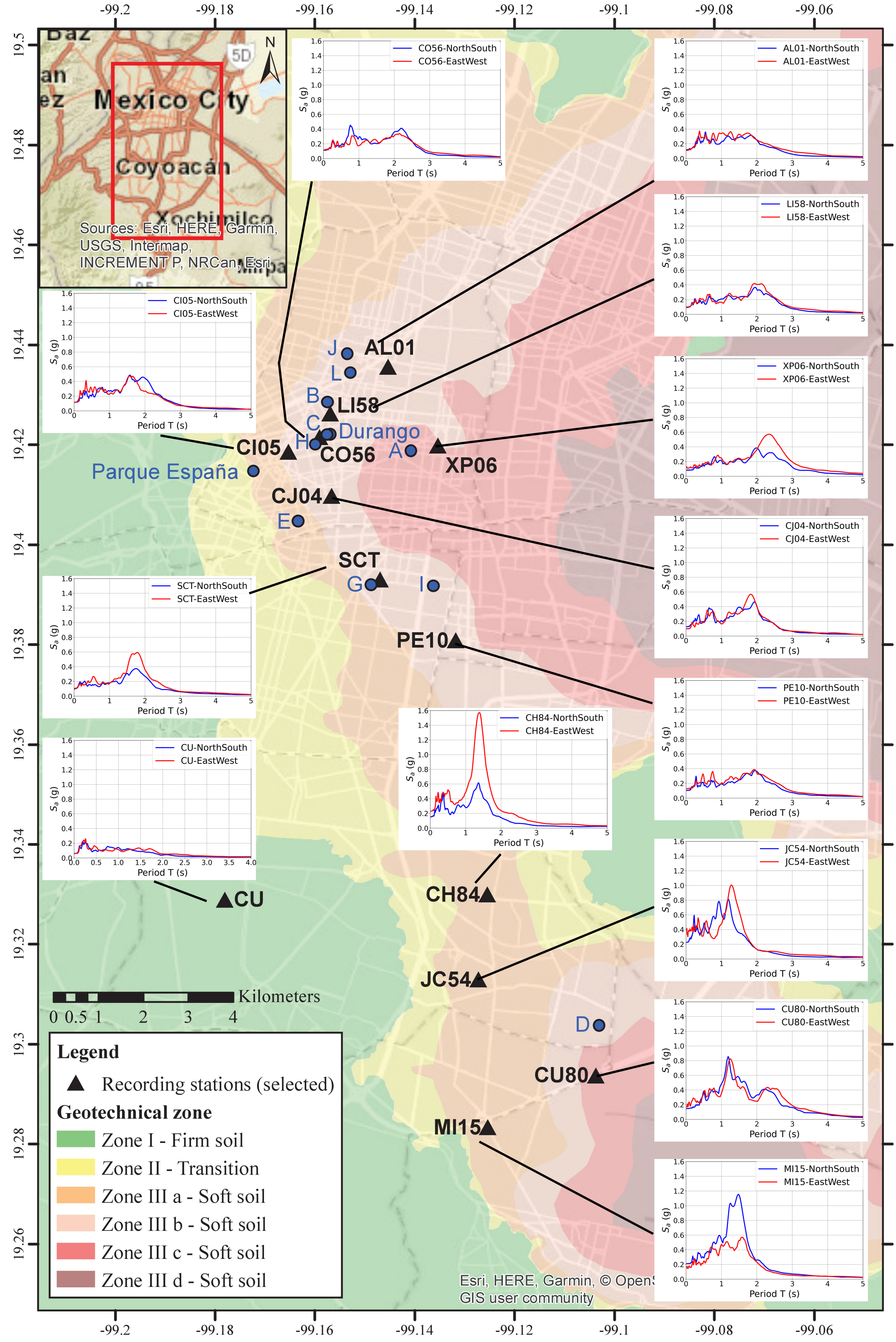
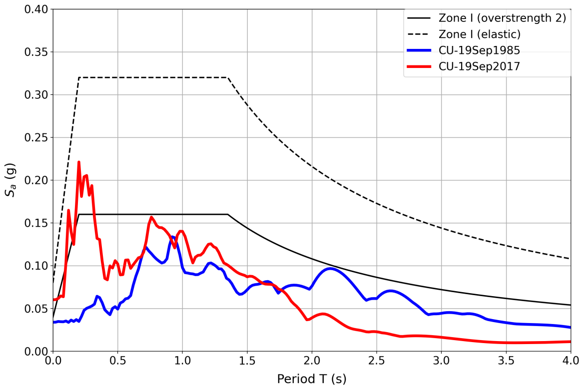
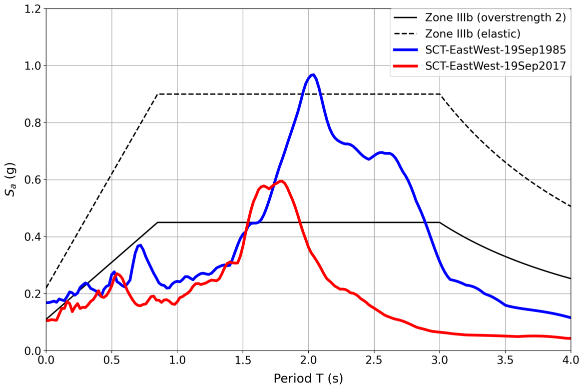


Figure 5: Major Sa values recorded in Mexico City.



(a) Response spectra at station CU (firm soil).



(b) Response spectra at station SCT (soft soil).

Figure 6: Response spectrum at stations CU and SCT for the 1985 Michoacán earthquake and 2017 Puebla earthquake.

Failure of Flat Slabs

While flat-slab systems were very popular in Mexico before 1985, after their brittle failure evident in the 1985 Michoacán earthquake, this configuration was not used after 1985. However, many buildings that suffered damage in the 2017 earthquake were built before 1985 and had this type of floor system. The waffle slab and precast beam-block floor systems were extensively used in Mexico [36]. Commonly, the thickness of a waffle slab ranged from 25 to 45 cm. Flat slab systems are flexible and prone to punching and shear failure the slab-column connections. Figure 10 shows an example of typical shear cracks observed in flat slabs.

Role of Masonry Infills

In Mexico, residential buildings typically have a significant number of infill walls of either brick or hollow clay tile. In several buildings, masonry infills between columns were observed to have failed. Infills are typically not considered in the design of RC frames in Mexico, and they are treated as non-structural walls. As is well-known, infill walls can significantly reduce structural drifts and the team suspects they may have protected many flexible flat slab buildings from exhibiting nonlinear response. If the seismic demands exceeded the strength of the infills, however, they would have failed in a brittle manner and concentrated damage to the frame would be expected. For the moderate demands of the 2017 Puebla earthquake, it is believed the infills may have helped reduce damage in many RC buildings, but for a larger earthquake the opposite may be true. In some cases though, X-shaped shear cracks were observed in masonry wall panels, as shown in Figure 11.

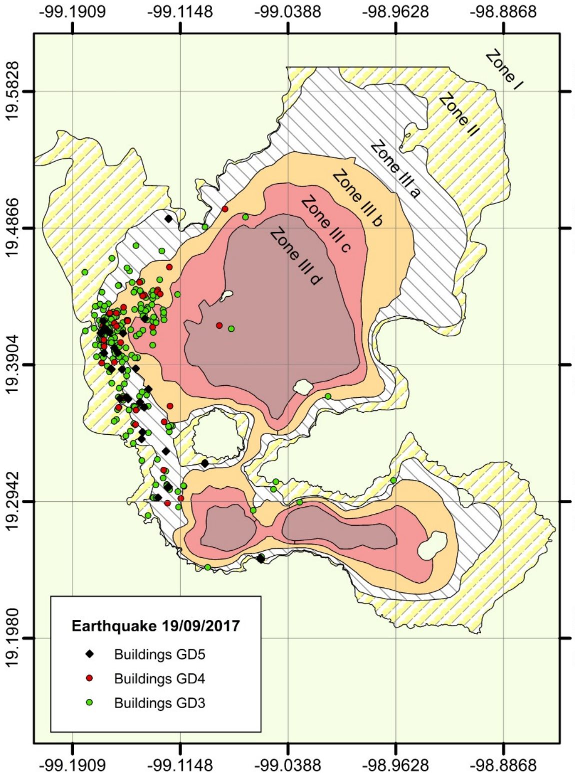


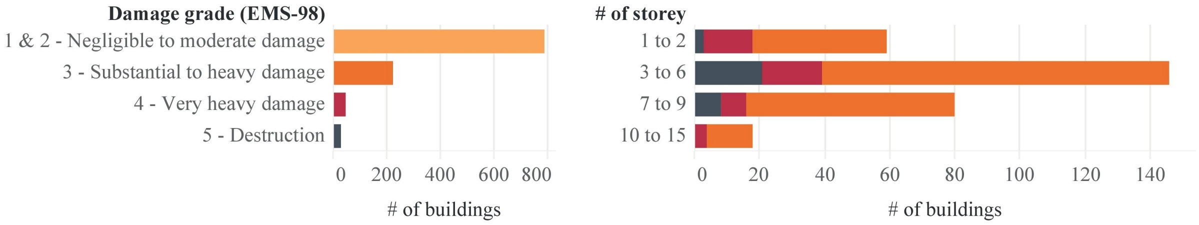
Figure 7: Map of the urban area of Mexico City showing buildings assessed by the UAM team. Damage was assessed according to the EMS-98 [33]. Dots represent building with damage grade 3 - substantial to heavy damage (green), damage grade 4 - very heavy damage (red), and damage grade 5 - collapse (black). The background overlay represents the geotechnical zones according to the code for Mexico City [20]: green for zone I (firm soil) , yellow with hatches for zone II (transition zone), white with hatches for zone III a (soft soil) , orange for zone III b (soft soil), and two shades of red for zones III c and III d (soft soil) [34].

Soft Storey Failure

Many buildings in Mexico City have an open ground storey reserved for parking. To allow for maximum space, any partition wall is removed in the ground storey, leaving only (slender) columns. This makes the first storey significantly softer/flexible (and in most cases weaker, too) compared to the upper floors comprising more columns and partition walls. Consequently, the drift demand in the ground storey will be larger than that of the upper storeys when subjected to a ground motion. If columns in the soft ground floor are weak or not detailed adequately to develop a ductile behaviour, they can lead to a storey collapse mechanism. This mode of failure was observed in come buildings, and an example is shown in Figure 12.

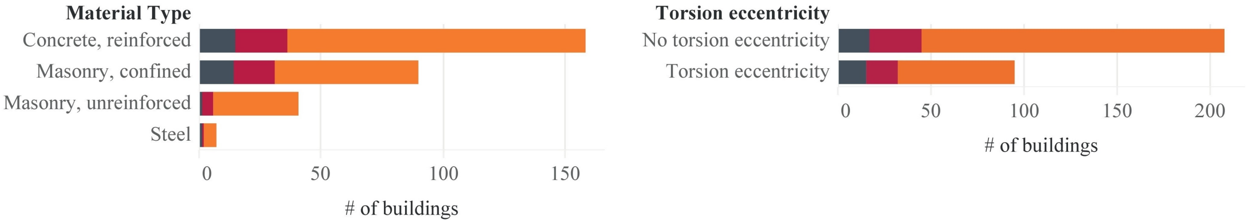
Damage Due to Interaction Between Adjacent Buildings

It is a common practice to leave sufficient clear space to prevent any interaction of two adjacent buildings during an earthquake. Nevertheless, Mexico City is a dense urban area where space is precious, so buildings are constructed densely with walls next to each other. In such circumstances, pounding between buildings is unavoidable in earthquakes as underlined by observations in other urban earthquakes [37]. Pounding is especially a problem when two adjacent buildings have two different heights or different dynamic characteristics. If they have different natural periods, there is a high probability they will behave differently



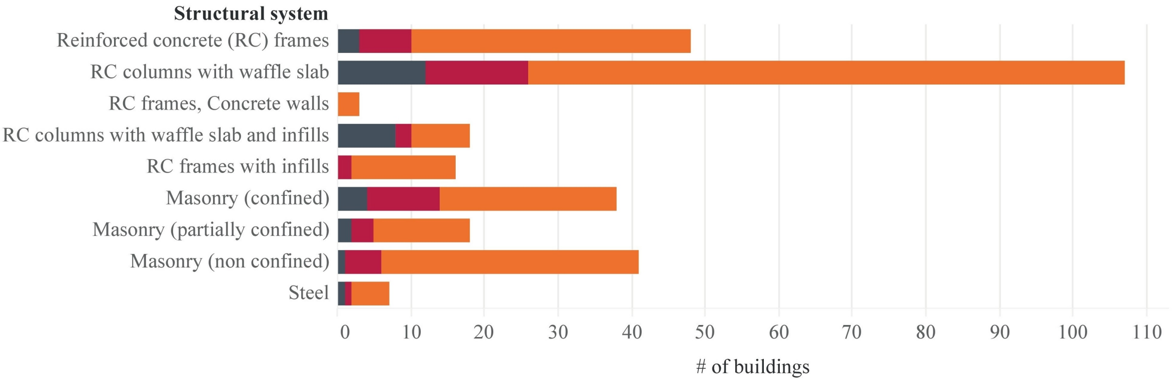
(a) Distribution of damage (# of buildings)

(b) # of storey (for damage grade 3 to 5)



(c) Material (for damage grade 3 to 5)

(d) Torsion eccentricity (for damage grade 3 to 5)



(e) Structural system (for damage grade 3 to 5)

Figure 8: Building damage statistics, adapted from [4].

under the same ground motion. The roof of the shorter building may collide with the exterior wall (or columns) of the taller one leading to severe damage. Figure 13b shows an example of observed pounding damage, where the shorter building suffered spalling and column damage due to a collision with the neighbouring taller building. Similarly, Figure 13b shows facade and infill masonry damage in the shorter building caused by the interaction with the taller building.

In some cases, two adjacent buildings were found to have restricted the motion of a taller building located in between. As shown in Figure 13c, the fifth floor of a seven storey building collapsed potentially due to interaction with the shorter adjacent buildings. The upper flexible part of the taller building oscillated while the lower part was more restricted from movement. Larger drifts in the upper storeys likely led to a concentration of inelastic demands at the fifth floor just above the roof of the smaller buildings.

Corner Buildings

Buildings located at the end of a block (or "corner buildings") have unique characteristics which increase their vulnerability. It is typical to have frames facing the streets and walls toward the rear of the building. This difference in stiffness leads to significant eccentricity between the centre of mass and the centre of resistance. Figure 14 shows two of the many corner buildings that suffered damage during this earthquake. The earthquake ground motion induced horizontal forces which generated torsion in these irregular buildings, causing extensive cracking in infill walls and severe damage to the non-structural claddings and columns.

Failure of Internal Elements

Most buildings visited by the team were inspected from the exterior only. For some buildings, building owners allowed the team to access and assess the internal elements. Nevertheless, most of the non-structural elements that had suffered damage during the earthquake had already been cleaned up when the team visited about a month later. As the insurance penetration of the Mexican

(a) *Shear failure in a column.*

(b) *Shear failure at the base of a column.*

(c) *Buckling of longitudinal reinforcing bars in a column.*

(d) *Spalling of concrete cover exposing large stirrup spacing.*

(e) *Lap-splice with insufficient length and confinement leading to debonding of concrete.*

(f) *Buckling of reinforcing bars in a concrete column.*

(g) *Column failure triggered by partial infill.*

Figure 9: Concrete column failures.

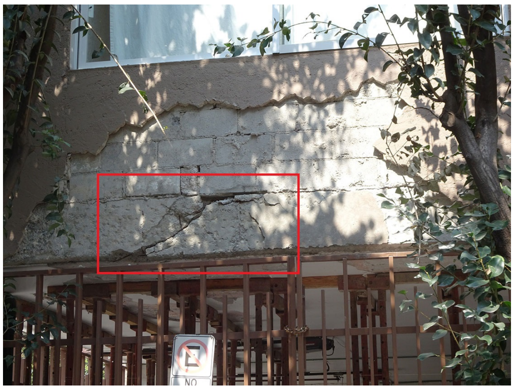


Figure 10: Slab failure.

market is low [35] and delays for insurance settlements were not an issue, people were understandably eager to clean up as soon as possible to be able to resume their businesses again and occupy their apartments.

Because of the limited internal inspection, drawing generic conclusions on the performance of non-structural elements was not possible. However, internal inspections were useful to check the performance of structural elements, partition walls and stairs. As shown in Figure 15 stairs and stairwells experienced damage due to the displacement of adjacent elements. Figure 15a and Figure 15b shows prefabricated stairs that fell off their support.

Figure 11: Failure in masonry wall.

A gap formed between the supporting slab and the prefabricated concrete stairs. This mode of stair damage was also observed in flexible RC buildings in Christchurch during the 2010-11 Canterbury earthquake sequence.

Figure 12: Soft storey failure leading to building collapse.

(a) Damage due to pounding between two buildings.

(b) Tilting of the left building leading to pounding.

(c) Storey collapse of level 5.

Figure 13: Damage due to interaction between adjacent buildings.

Conclusions on Structural Damage in Mexico City

Among the damaged buildings only a few were new buildings (2013-2017), some were built in the period 1987-2012 and the rest were constructed pre-1985 with structures dating back to 1950s, 1960s, 1970s, and 1980s. Despite the very few cases of new buildings which suffered partial collapse and heavy damage, the limited extent of damage in new buildings emphasised the improved seismic performance of recent buildings. Retrofitted buildings also behaved well. In some cases, it was clear that the retrofit protected the building from being heavily damaged or collapsing.

To reiterate the well-established theory, RC buildings with good structural configuration that avoids irregularities and load concentrations along with proper ductile detailing will perform better in earthquakes. This was further proven in this earthquake as most new buildings (which had better configuration and detailing) were observed to have performed well with limited or no damage.

(a) Corner building heavily damaged.

(b) Damage on the North facade.

(c) Corner building to the point of collapse.

(d) View of the corner between the South and West facade.

Figure 14: Damage in corner buildings.

(a) Stairs failure (front view).

(b) Stairs failure (side view).

Figure 15: Failure of internal elements.

PERFORMANCE OF RETROFITTED BUILDINGS

Performance of Retrofitted Concrete Buildings

The 1985 Michoacán earthquake led to extensive damage in Mexico City. For damaged buildings, wherever possible, the building's owner tended to avoid demolition and rather chose to repair and retrofit the buildings. Various documents following the 1985 earthquake explain the techniques and solutions employed to reinforce and retrofit the structures [30, 36, 38–41].

The upgrading of critical structural elements with steel strapping and/or concrete jacketing was a typical retrofit or repair used to add deformation capacity to the critical elements. In addition to retrofits after 1985, the NZ team observed several buildings where steel strapping was being installed in October 2017. Steel straps are intended to provide concrete confinement to improve their ductility and shear strength without changing the lateral force-resisting mechanism of a building [42]. Steel strapping is flexible and adaptable to different shapes of columns (Figure 16). Epoxy resin ensures the connection at the interface between the steel strap and the concrete column. The case studies show more examples of steel column jacketing from after the 1985 earthquake.

(a) Steel jacketing of box concrete columns.

(b) Steel jacketing of circular concrete columns.

Figure 16: Steel jacketing.

Following the 1985 earthquake, many high-rise buildings were retrofitted with external braces. The objective was to reduce the overall building displacement without increasing the stress on the foundation to an extent that would require difficult and expensive foundation strengthening measures. Walls were less common due to concerns of large foundation forces in soft Mexico City soils. Bracing was used to modify the building natural period and shift the structure out of the critical 1-2 second period range for soft soil sites. Figure 17 shows one such braced building in the neighbourhood of La Roma. The brace is anchored at the base and attached to the building at one third of the height and at the rooftop.

Figure 17: External bracing system.

The NZ team visited a few schools in Mexico City, in which the structural design was relatively similar consisting of reinforced concrete frames. These concrete frames were mostly filled with masonry in the lower half and the upper half was left as an opening for windows. It seems that for most of these schools, the design engineers did not consider the masonry infill in the lateral load resistance of the building and only accounted for the RC frames to resist earthquake loading. However, if an adequate gap between the frame and the masonry is not provided, the masonry infill will influence the behaviour of the RC frame, often leading to damage.

The 1985 Michoacán earthquake had already exposed the vulnerability of schools in Mexico City. Following the 1985 earthquake, the government initiated widespread retrofit of school buildings. The retrofit measure implemented in one of the visited schools is shown in Figure 18a. The braces added stiffness and strength to the structural frame. Although they were able to prevent collapse of the building and ensured life safety during the 2017 earthquake, they were not able to avoid damage to infill walls. Figure 18b shows an out-of-plane failure of a masonry infill wall in the same school, emphasising the importance of bracing out-of-plane walls.

(a) Internal bracing of a frame.

(b) Out of plane failure of the masonry wall in a school building.

Figure 18: Performance of retrofitted school buildings.

Figure 19 shows another school building where external steel cable braces were added in front of the exterior frame. The external braces aim to reduce the overall displacement of the building and thus limit the damage during an earthquake. The braces span two stories. To let the brace through, the slabs were drilled. Concrete grout was used to reinforce the end connection. This school building performed well during the 2017 earthquake.

Figure 19: School building previously retrofitted with external steel braces.

Retrofit Studies from Aguilar et al., 1996

Aguilar et al. (1996) published case studies on retrofitted reinforced concrete buildings. These buildings were damaged in 1985 during the Michoacán earthquake. They were then repaired and retrofitted with different solutions as explained in a University of Texas report [38]. Table 1 presents a list of these buildings. Ten buildings are located in the centre of Mexico City (3 in the neighbourhood north of Paseo de La Reforma, 3 in La Roma, 2 in Narvarte Poniente, 1 in the neighbourhood of Doctores, and 1 in the south in Xochimilco).

Following the 2017 Puebla earthquake, the NZ team assessed the performance of these buildings. Only an exterior inspection was possible in most cases. From an external inspection, all the structural elements seem to have performed well. Most buildings were inhabited when the 2017 earthquake happened. Building owners who could be contacted did not report any damage, not even to non-structural elements. The following sections describe the retrofits and observations from NZ team inspections.

Building A

This four-storey tall warehouse is located in seismic zone III c (lake bed zone). The reinforced concrete frame building was built in 1959. The building suffered damage to beams and columns during the 1985 earthquake. Columns and beams were retrofitted with reinforced concrete jacketing.

At the date of inspection, doors were closed, and it was not possible to enter the building to check the retrofitted columns. The outside facade showed no apparent damage. As can be seen in Figure 20, the building seemed to have performed well during the 2017 Puebla earthquake.

Building B

This 11-storey tall commercial and residential building was constructed at the end of the 1960's. It is in the neighbourhood of La Roma, one of the most affected neighbourhoods during the 1985 and 2017 earthquakes. The main structural system was RC waffle slabs and columns. The building did not experience any structural damage during the 1985 earthquake; however, the flexibility of the structure led to damage in the non-structural elements. To reduce this flexibility, external bracing elements were attached on the facade of the building. Figure 21a shows the elevation of the building and gives a view of the braces. As shown on Figure 21b, diagonal elements span four floors and are connected to corner columns with steel plates (covered for aesthetics).

As the first floor is used for commercial purposes, it was possible to do an internal inspection of some parts of the first floor. The building did not suffer internal or external damage during the 2017 earthquake. A discussion with a shop owner from the first floor confirmed that non-structural elements did not experience any damage during the 2017 earthquake. The retrofit solution performed as expected leading to low overall displacement of the structure and protection of the internal elements.

(a) Front view.

(b) Side view.

Figure 20: Building A.

(a) North and East facades.

(b) Middle connection of the bracing system.

Figure 21: Building B.

Table 1: List of retrofitted case study buildings, after [38].

Building	Zone (see Fig2b)	Number of stories	Structural system	Strengthening/ Repair	Nearest station ID	Nearest station name	PGA (g)
A	III c	4	RC frame	Beam and column jacketing with RC	XP06	Jardín de Niños Xochpilli	0.11
B	III b	11	RC columns, waffle slab	Exterior steel diagonals and beams	LI58	Escuela Secundaria Diurna No. 23	0.10
C	IIIb	12	RC perimeter frame and RC shear walls	Removing of the four top floors (mass reduction)	CO56	Escuela Secundaria Técnica No. 18	0.12
D	III b	4	RC columns, waffle slab	Cable bracing system in longitudinal direction	CU80	Escuela Primaria Aurora López Velarde	0.17
E	III a	7 (north unit), 8 (south unit)	RC columns (1st floor), Confined masonry walls (upper floors)	Addition of RC frames, Upgrading of existing beams and columns	CJ04	Multifamiliar Juárez II	0.13
F	III b	6	RC frames with haunched beams	Addition of RC walls			
G	III b	11	RC columns, waffle slab and RC shear walls	Addition of two RC infill walls	SCT	Secretaría de Comunicaciones y Transportes	0.11
H	III b	7	RC columns, waffle slab	Addition of RC walls, Concrete jacketing of columns in the lower stories	CO56	Escuela Secundaria Técnica No. 18	0.12
I	III b	4	RC frames	Addition of concrete walls, Recast of columns, Beam jacketing at the joints	PE10	Escuela Primaria Plutarco Elías Calles	0.13
J	III b	6	RC columns, waffle slab	Steel bracing of the middle frames, Steel jacketing of the boundary columns	AL01	Alameda	0.12
K	II	16	RC columns and RC walls	Steel braces, Reinforcement of the columns bounding the braced bays			
L	III b	14	RC frames	RC walls, Steel braces	AL01	Alameda	0.12
Durango	III b	12	RC frames	External steel braces	CO56	Escuela Secundaria Técnica No. 18	0.12
Parque España	III a	10	RC frames	Diagonal steel cross bracing in the central bay	CI05	Roma	0.12

Building C

Building C is in the neighbourhood of la Roma Norte in the seismic zone III b. This 12-storey building is in front of a hospital and serves as a medical office. Figure 22a shows the building in elevation. The structural system is a mixed system of reinforced concrete perimeter frame and concrete shear walls. During the 1985 Michoacán earthquake, RC beams in the longitudinal frames experienced damage. The adopted retrofit measures were diverse. First, to reduce the overall mass of the building, the top four floors were removed. Second, columns were upgraded with additional reinforcement, and the third measure was to post-tension the deep beams in longitudinal direction. In Figure 22b, it is possible to observe the end of the post-tensioning cables. The exterior inspection revealed no damage after the 2017 earthquake.

Building D

Building D is the only retrofitted building assessed by the team in the southern part of Mexico City; nevertheless, it is in the lake bed area in seismic zone III b. Concrete columns and a reinforced concrete waffle slab formed the original lateral load resisting system of the building. It is a school building owned by

(a) Side facade. *(b) Zoom on the end anchors of the post-tensioning cables.*

Figure 22: Building C.

the Metropolitan Autonomous University (UAM). In the 1985 earthquake captive columns experienced diagonal cracks wider than 1 mm. As a retrofit solution, engineers decided to add cable braces acting in tension, as shown in Figure 23. The cable braces were designed such that the cables and the original RC frame reached their maximum lateral resistance at approximately the same horizontal displacement. Columns were strengthened to withstand the added loads due to the cable bracing. New steel beams were used to strengthen the diaphragm at the stairwell openings. Reinforced masonry walls located in the stairway areas were also reinforced with wire mesh and shotcrete.

Cable braces and steel beams performed well during the 2017 earthquake. No damage occurred in the braces and structural elements or in the non-structural walls.

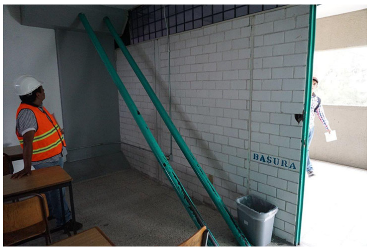


Figure 23: Building D - Cable bracing and connection through slab-column joint.

Building E

This building located in the southern part of La Roma neighbourhood is in seismic zone III a. Constructed in 1979, the building has a C-shaped plan with two residential units linked by a core with stairs and elevators. One unit has seven stories and the other has eight stories. Figure 24 shows views in elevation. As is typical in Mexico City residential buildings, the ground floor has a different layout and structural system than the rest of the building as it is devoted to parking. To save space, concrete columns in the ground floor replace the confined masonry walls present in the upper floors. The first floor above ground is a waffle slab, while all other floors use a beam-block floor system. In the 1985 earthquake, damage occurred due to irregularities and failure of the masonry infills in the shorter direction of the building. The retrofit measures consisted of the addition of concrete frames and the upgrading of existing beams and columns.

Following the 2017 Puebla earthquake, the external inspection did not reveal any apparent damage to the facade facing the street, nor the perpendicular direction. The building is narrow and C-shaped. An internal inspection would have enabled checking the behaviour of the retrofitted elements; nevertheless, inner access was not granted.

(a) Front facade. *(b) Side facade.*

Figure 24: Building E.

Building F

Inspection of this building was impossible as no information on the building location was available.

Building G

The building is located in the neighbourhood of Narvarte Oriente in the lakebed zone of Mexico City (seismic zone III b), 300 m away from the SCT recording station (response spectra shown in Figure 6b) and 1.70 km away from the station PE10 Escuela Primaria Plutarco Elías Calles operated by CIRES. The 11-storey office building was constructed in 1980. Figure 25b shows the facade of the building. The structure consists of reinforced concrete columns and a waffle-slab floor system. Additionally, reinforced concrete shear walls are present along the north and south boundaries of the building and in the elevator core. The foundation is composed of a box and a mat foundation, 1.5 m deep, supported by friction piles. Non-structural masonry infills were also present.

The building suffered localised damage in the North-South direction of the building in the 1985 Michoacán earthquake, with the boundary walls in the East-West direction performing well. The retrofit measures consists of the addition of reinforced concrete infill walls as well as steel and concrete jacketing of the end-columns, as shown on Figure 25b.

Following the 2017 Puebla earthquake, external and internal inspection of the building were possible. No structural or non-structural damage was observable.

Building H

The building is located in the neighbourhood of La Roma Norte in seismic zone III b. The 7-storey office building was constructed in 1975. The floor system is a waffle slab supported by reinforced concrete columns. The 1985 earthquake damaged the columns of the building. The retrofit solution consisted of the addition of concrete walls (extending from basement to the roof) and the concrete jacketing of the columns up to level 5; levels 6 and 7 were not retrofitted.

After the 2017 earthquake, only an external inspection was allowed. An internal inspection to check the column was not possible. It would have been interesting to see the performance of the jacketed columns in level 1 to 5 (70 x 70 cm) versus the columns in the levels 6 and 7 (45 x 45 cm) that were not retrofitted. Nevertheless, as shown on Figure 26, no damage occurred in the glass cladding suggesting that the building performed well during the Puebla earthquake.

(a) Front facade. (b) RC columns reinforced with steel.

Figure 25: Building G.

Figure 26: Building H - Glass cladding on the main facade.

Building I

The four-storey building owned by one of the national telecommunication companies is located in the neighbourhood of Moderna in seismic zone III b. As shown on Figure 27, in its original configuration the building is asymmetric in plan leading to torsional effects under earthquake loading. Due to torsion in the building during the 1985 earthquake, corner columns, as well as beam-column joints and beams, were damaged on one side of the building. Extensive concrete spalling had also occurred throughout the building. Following the Michoacán earthquake, the telecom company decided to retrofit all its buildings to guarantee a continuous service during future earthquakes. For this building, structural engineers decided to add concrete walls, recast some columns, and apply concrete jacketing at the joints.

Following the 2017 earthquake, no internal inspection was possible. The exterior inspection was also limited due to walls around the building. Nevertheless, the inspection of one exterior facade revealed no apparent damage. The building appeared to have performed well during the 2017 Puebla earthquake.

Building J

This six-storey office building was constructed in 1974. It is located in the north of Paseo de la Reforma in seismic zone III b. The structural system is a waffle slab supported by reinforced concrete columns. The material for the partition walls is solid clay brick masonry. The building is C-shaped in plan. Apart from minor cracking, the building did not experience notable damage during the 1985 earthquake. Nevertheless, the building owners decided to retrofit the building to meet the new seismic standards of the 1985 Emergency Norms [26]. For retrofit, the owner opted for the addition of steel bracing in the middle frames, steel jacketing of the boundary columns and strengthening of the masonry walls. Figure 28 shows the external bracing on the facade.

After the 2017 earthquake, only an exterior inspection was possible. Damage on the façade or in braces were not observable. The building seemed to have performed well.

(a) Front view.

(b) Side view.

Figure 27: Building I.

Figure 28: Building J - External bracing on the facade.

Building K

Inspection of this building was impossible as no information on the building location was available.

Building L

This 14-storey building located on Paseo de la Reforma, seismic zone III b, was built before 1957. The structural system is composed of reinforced concrete frames with solid concrete slab. During the 1985 earthquake, columns near the elevator had suffered severe damage. Cracks had also formed in the slabs and beams of all stories as well as in the masonry partition walls. The retrofit solution proposed was to remove the two top levels and change the floor finishes of the slab in order to reduce mass in the building. However, building owners decided to increase the stiffness of the building without changing the building configuration. They built additional concrete walls and added steel braces in some of the frames.

In the 2017 earthquake, the external inspection revealed no damage to the facade. Steel bracing was only observable through the windows (Figure 29). No internal access allowing a closer look at the braces was granted.

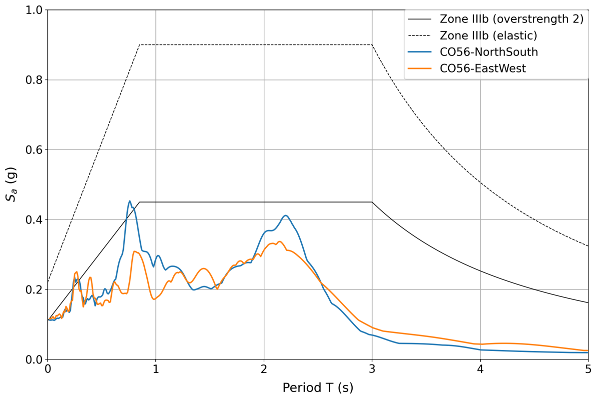
Figure 29: Steel bracing in upper levels behind the facade (building L).

Key Studies from Foutch et al., 1989

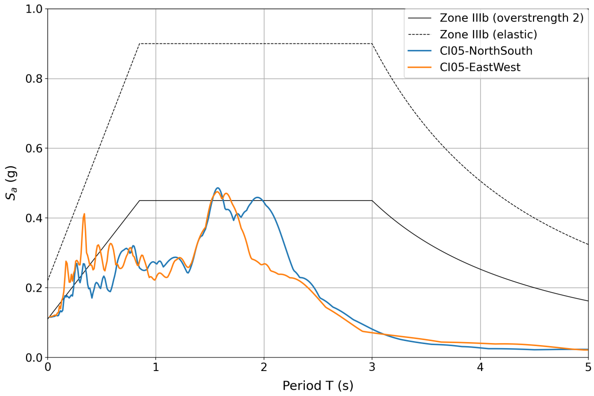
Foutch et al. (1989) [40] extensively studied the case of two retrofitted buildings located in the most affected neighbourhood of Roma and La Condesa. Although not far from each other, they are not located in the same seismic zone of the 2004 Mexican building code. The first building on Durango street, is in the III b zone while the building in Parque Espana is at the boundary between zone III a and the transition zone II.

Figure 30 presents the acceleration spectra of the North-South and East-West motions recorded at station Roma (CI05) and station Escuela Secundaria Tecnica No. 18 (CO56). A comparison of the two graph shows that the maximum peak spectral acceleration is between 0.4 g and 0.5 g. Nevertheless, the peak occurs at different periods in these records. While the station CO56 shows two peak accelerations, one at 0.76 second of 0.45 g and the other at 2.2 seconds of 0.41 g, the maximum acceleration for CIO5 is 0.49 g at a period of 1.57 seconds. For the latter, the value exceeds slightly the plateau of the design spectra.

In the 1970's and 1980's, the network of recording stations was not as extensive as in 2017. The most representative recording station for buildings in the neighbourhood of Roma and La Condesa was the SCT station located further south. Figure 31 shows the recordings for the 1985 Michoacán and 1979 Guerrero earthquakes at this station.



(a) Station CO56.



(b) Station CI05.

Figure 30: Response spectrum for the 2017 Puebla earthquake.

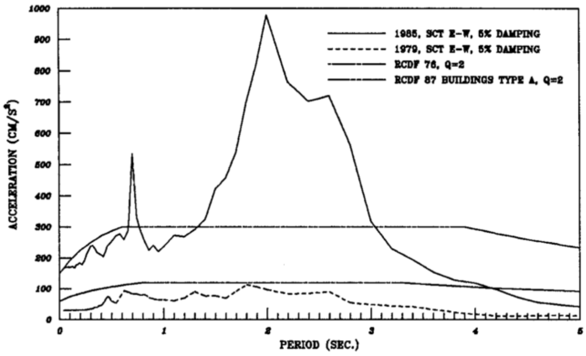


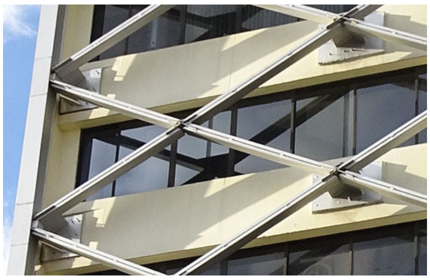
Figure 31: Acceleration response spectra for the 1979 and 1985 earthquakes and the Mexico City design spectra for the lake-bed zone [40].

Building Durango: External Steel Bracing

The 12-storey building located in the Calle Durango houses medical laboratories. It is a reinforced concrete frame building. The foundation is a concrete box on friction piles. The M 7.6 Guerrero, Mexico 1979 earthquake induced extensive damage in the short-direction (east-west) of the building. Cracks formed in the columns in the lower stories. Concrete cracking and spalling also occurred in the beam-columns joints. Diagonal cracks appeared in the spandrel beams. Damage concentrated mainly in the outside frames due to their higher stiffness provided by the spandrel beams. As retrofit measures, steel braces were added on both facades in the short direction (Figure 32). This led to an increase in stiffness in the east-west direction. Additionally, reinforced concrete infill walls increased the strength of the building in the north-south direction. Steel plates were used to strengthen columns which experienced shear and flexural cracks. The diaphragm was also reinforced. It is important to mention that these additional measures only increased the weight of each floor by an average of 6.5%.

The NZSEE team after the 1985 Michoacán earthquake reported on the performance of this building in the 1985 earthquake. No damage was reported. The stiffer steel frames changed the building period away from the critical period range of 2.0 seconds. The exterior inspection following the 2017 earthquake did not identify any apparent damage to the facade or braces. Once again, the structural retrofitting seemed to have performed well.

(a) Exterior steel bracing.



(b) Detail of the steel connection.

Figure 32: Building Durango.

Building Parque España: Internal Steel Bracing

The second building analysed in the Foutch paper is located in the neighbourhood of Roma Norte near the Parque España. It is a 10-storey residential building (Figure 33a) designed and constructed with moment frames and waffle slabs.

Similar to the Durango building, this building was damaged during the M7.6 1979 Guerrero earthquake. The building was flexible leading to large deformations which resulted in pounding with one adjacent building and damage to the exterior columns and walls. The building suffered little damage during the 1985 earthquake. Minor pounding led to damage in the brace connection at the level of pounding as well as cracking and spalling in the partition walls and plaster.

The objective of the retrofit measures was to add stiffness and strength to minimise the overall building displacement. Engineers decided to add diagonal steel braces in the middle frame (Figure 33b and Figure 33c). Additional RC infill walls in the external bays along the longitudinal direction also played a significant role in the increase of the stiffness and strength in the longitudinal direction of the building. As the retrofit led to an increase of 3% of the storey weight only, it was not necessary to add any piles.

The nearest seismic recording station (850m away from the building) is the CI05 in la Roma. Despite the relatively close distance, the CI05 station is in a different seismic zone. The building itself is located at the border of the transition zone and the zone III a. Soil conditions below the building are thus not clear and further analyses are required. Seismic recording in the proximity of the building would provide valuable information. The retrofits shifted the building period to T = 1.1 s and T = 0.90 seconds for the first mode shape of the north-south and east-west direction, respectively [40]. The measures were therefore effective in shifting the building away from the critical T = 2 s period in the 1985 earthquake..

Following the 2017 Puebla earthquake, the building manager allowed an inspection of only the 1st floor. Braces themselves had not suffered any apparent damage. Minor damage was observable on the external facade of one frame near the slab column brace joint but overall, the building performed well during the 2017 Puebla earthquake.

(a) View in elevation.

(b) Internal steel bracing in frames 1 and 2.

(c) Internal steel bracing in frame 3.

Figure 33: Building Parque España.

Colegio Madrid

Colegio Madrid is a private school complex of more than 15 buildings, oldest dating from 1941. In the early 1980's, some new buildings were constructed. The school had finished construction and payments by January 1985, and the buildings were ready for the beginning of school in September 1985. But on September 19th, 1985, some of these buildings suffered extensive damage.

Following the 1985 Michoacán earthquake the multi-storey secondary and high school buildings (red square in Figure 34) were evacuated as they had experienced severe damage. These buildings were subsequently repaired and retrofitted with steel jacketing and steel braces. The yellow rectangle shows the location of the primary school which was retrofitted at a later stage with concrete walls. In the green rectangles are all the buildings (administrative buildings, library, kindergarten) which did not suffer any damage during the 1985 Michoacán earthquake. These buildings were one or two-storey structures and no strengthening was done on these buildings.

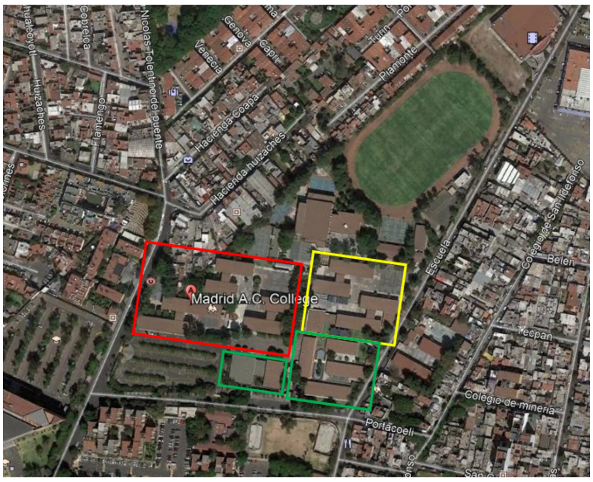


Figure 34: Colegio Madrid; Red square indicates buildings damaged in 1985 and repaired and retrofitted; Yellow square indicates buildings retrofitted after 1985; Green squares indicate buildings not retrofitted in 1985. Only buildings in green squares were damaged in 2017.

Seismic Demand near Colegio Madrid

Colegio Madrid is located at the border between the transition zone and seismic Zone III a. CIRES operates three seismic stations nearby in zone IIIa. The variation in the NS and EW components is evident in the recorded spectra (Figure 35). For all cases, however, as buildings with periods between 0.5 to 1.0 s soften with damage, the intensity of shaking is likely to increase.

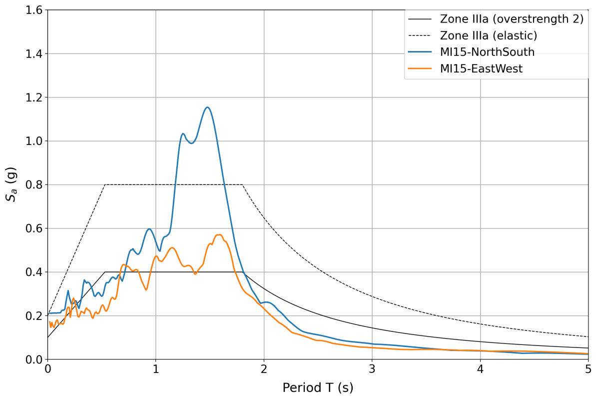
Colegio Madrid Damage in 2017

The multi-storey buildings that were repaired and retrofitted after the 1985 Michoacán earthquake performed well, and suffered no damage in the 2017 earthquake (Figure 36). However, the 1-2 storey buildings that were not retrofitted following the 1985 earthquake, experienced extensive damage during the 2017 earthquake. The library (1-storey) and administration (2-storey) buildings were separated through a construction joint. Nevertheless, the administration building suffered damage (Figure 37a and Figure 37b). The four kindergarten buildings, which are 1-storey buildings, suffered extensive damage during the 2017 Puebla earthquake as shown in Figure 37c.

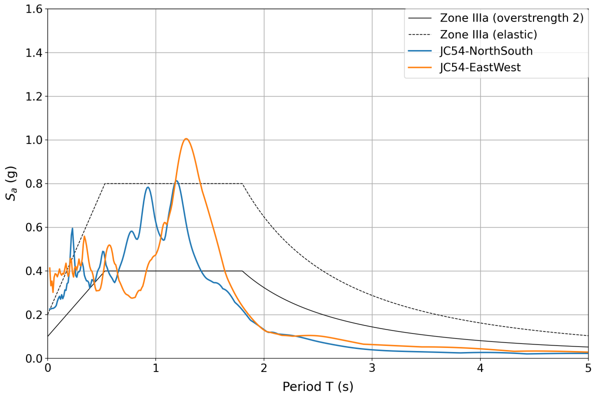
During the visit of the NZSEE team at the end of October 2017, repair and retrofitting works were already in progress. Builders had to create openings at the base and the top of the columns to ensure a proper connection of the grade beams and slab at the joints with the columns. Figure 38 shows the new column reinforcement.

Conclusions on Retrofitted Building Performance

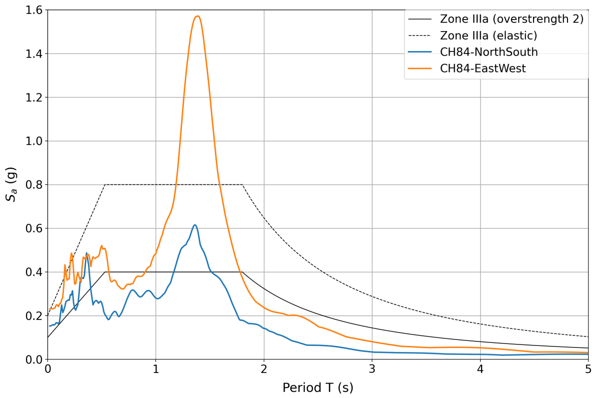
For the 2017 Puebla earthquake, all the surveyed buildings which were previously retrofitted performed very well. No or very minor damage to the structural elements were observable. In contrast, unretrofitted buildings with structural deficiencies sometimes experienced extensive damage.



(a) Record from station MI15. North-South component is dominant.



(b) Record from station JC54. East-West component is dominant.



(c) Record from station CH84. East-West component is dominant.

Figure 35: Response spectrum for the 2017 Puebla earthquake.

The objective of most retrofit solutions was to shift the period of the building out of the critical range for the soft, deep Mexico City soils. In some cases, the aim was to reduce the overall building drift without increasing too much the demand on the foundation. While this limited intervention approach was achieved by using steel bracing over the entire height of a building, retrofits employing additional reinforced concrete shear walls required an upgrading of the foundation with additional piles.

(a) No damage in the previously retrofitted high school building.

(b) No damage in the building retrofitted with concrete walls.

(c) No damage in the primary school retrofitted with concrete wall.

Figure 36: Colegio Madrid buildings retrofitted after the 1985 Michoacán earthquake.

(a) Shear crack in a column of administration building. *(b) Shear crack in a column of administration building.*

(c) Damage to a column in the Kindergarten.

Figure 37: Colegio Madrid buildings damaged during the 2017 Puebla earthquake.

(a) Repair and retrofit of columns. *(b) Repair and retrofit of columns.*

Figure 38: Colegio Madrid - Repair and retrofit of columns by concrete jacketing - addition of steel reinforcement

EARLY WARNING SYSTEM

Overview

Following the aftermath of the 1985 M8.0 Michoacán earthquake, the Mexican government decided to develop an early warning system to monitor the Guerrero seismic gap [43]. The construction of an Early Warning System was completed and came into operation in 1993 with twelve sensors located along the coast of the Guerrero state [44, 45]. Four major modules compose the Mexican Seismic Alert System (SASMEX): the seismic detector system, the communication system, the central control and registry system, and the warning dissemination system (Figure 39). The seismic detector system was initially designed to capture earthquakes originating in the subduction zone along the Middle America Trench, but the system evolved over the years. In 2017, the SASMEX network counted 97 active stations [45]. Some stations are now located inland in the central part of Mexico, but the significant number of sensors remain situated along the southwest Pacific coast of Mexico (Figure 40). If the sensors record a significant ground motion in their area, they send a signal to the central control via the communication system made of radio relay. The signal is then dispatched from the central control to sirens and devices connected to the early warning system.

Alert in Mexico City

Once the sensors record a signal and deem it as a potentially dangerous earthquake for Mexico City, the preventive alert is given. Figure 40 shows a map with the sensor locations. Based on the distance from Mexico City, black circles represent the amount of time between the warning and the moment the earthquake will shake the capital (time-till-shaking). For an earthquake starting along the south west Pacific coast, there are about 55-60 seconds between the start of the preventive alert and the arrival of the first seismic wave in Mexico City. From Figure 40, we can also observe that the density of sensors located inland is lower compared to the coastal area. Despite the few stations located near the epicentral area of Morelos, the alarm went off in the afternoon of September 19th, 2017.

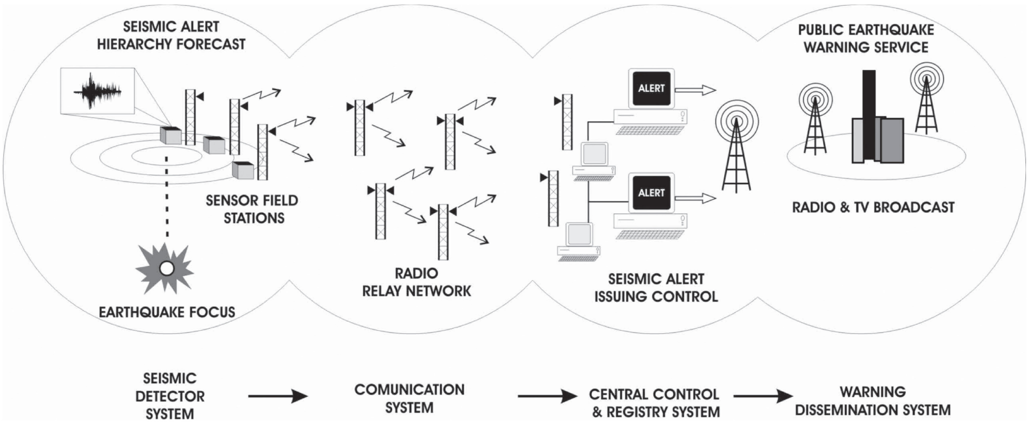


Figure 39: Overview of the Mexican Seismic Alert System (SASMEX) [43].

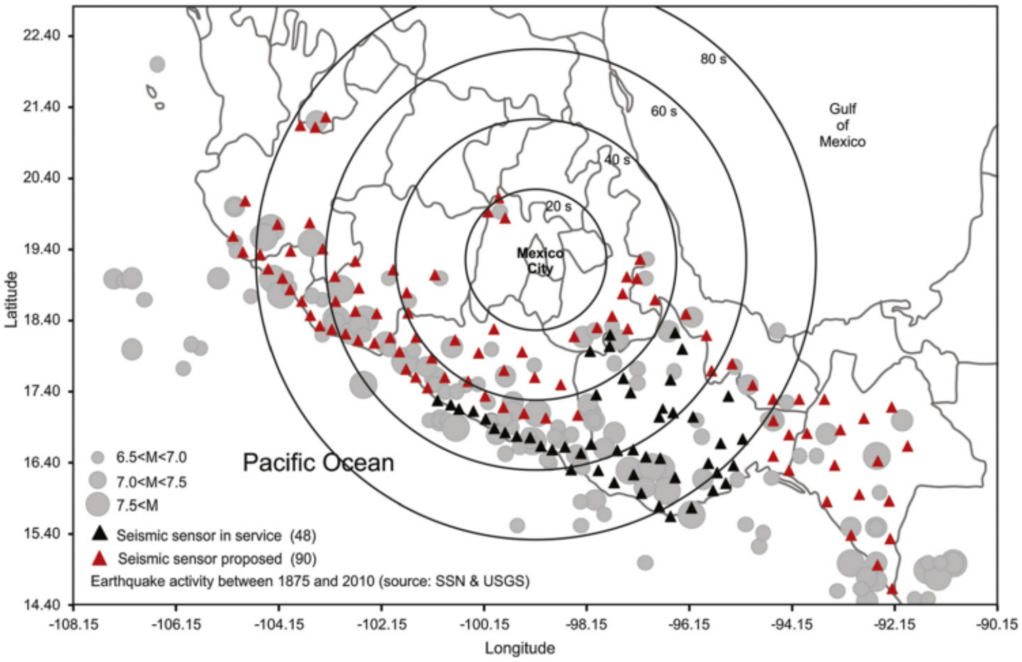


Figure 40: Visualization of the available prevention time in Mexico City dependant on the hypocentre location [44].

The Early Warning System During the Puebla Earthquake

Mexico City experienced five alerts during September 2017. On 6th September, a technician accidentally, triggered sirens across the city. One day later, the alarm went off due to the M_W 8.1 Chiapas, Mexico earthquake that originated in the Gulf of Tehuantepec. The epicentre was located over 700 km away from Mexico City giving a prevention time of about two minutes. Even though the shaking was widely felt, little damage occurred in Mexico City. On 19th September, at 11 am the alarm was triggered as part of the annual earthquake drill in commemoration of the 19th September 1985 Michoacán earthquake anniversary. This year, the sirens sounded again 2 hours later, at 1:15 pm, because of the M_W 7.1 Puebla earthquake with an epicentre 120km from Mexico City. Due to this relatively close proximity of the epicentre to Mexico City, the prevention time was very short compared to typical earthquake originating along the south-west coast. In fact it was reported that the sirens were heard sounding after the arrival of the primary wave, but before the secondary wave [46]. Anecdotally, it was reported that some people did not respond to the alarm as they thought it was a false alarm after the annual drill earlier in the day. The last alert sounded on the 23rd September 2017 at 7:53 am for the M 6.4 earthquake again originating more than 700 km in the south of Mexico. Among the five alerts of September 2017, one was false, one was part of the annual anniversary drill, one came later than the first seismic wave, and two were successful. Coincidentally, the successful alerts were for earthquake events with little consequences for the capital [46].

The SASMEX and the Population

The first objective of an early warning system is to alert the population of an approaching ground motion, but an early warning system should also contribute to making people more aware about earthquake risks, impacts, and how they should react during the prevention time [47]. A warning system is only effective if the population reacts appropriately during the prevention time. Therefore, earthquake disaster preparedness is necessary. Authorities must ensure that people have sufficient knowledge and information regarding appropriate actions to follow once the earthquake alert is triggered. Nevertheless, there appeared a lack of clear public policies and protocols regarding the required actions during the prevention time. The instructions for the public in Mexico City is to go out of the building and wait at specific gathering points deemed safe. However, concerns exist about damaged elements that could fall in some of these 'safe' gathering areas. Furthermore, leaving the building may be feasible and appropriate for distant earthquakes with long time-till-shaking, but for closer events such as the 2017 Puebla earthquake, leaving buildings was frequently neither feasible nor safe.

The first alert needs to be short and simple to be understandable by everybody. Information that is more complete should follow in the minutes after the first alert. The 2017 Puebla earthquake demonstrated the impact of social media and the key role it played in informing the population. Thus, it is necessary to ensure that news and information communicated on social media are accurate and consistent in order to prevent confusion [47].

In general, people receive the earthquake alert positively. Most people the team talked to described the system as valuable and necessary, some even described it as stupendous. But the population is also aware that the system is not perfect (e.g. technical limitations). Nevertheless, they see the benefit of protection first. They tolerate some false events and accept some technical issues [46].

KEY OBSERVATIONS AND LESSONS

While the dominant damage to non-ductile concrete buildings may not be new and simply reinforces the lessons from so many prior earthquakes, the 2017 Puebla Earthquake did leave key impressions on reconnaissance team which relate to earthquake engineering practice in New Zealand. The following briefly summarises some key observations related to demands in soft soil sites and basins, the role of infill walls, and the performance of retrofitted buildings.

The ground motions recorded on different zones (classified based on site characteristics) clearly showed spectral amplifications at/around the site period, and buildings with periods matching the site periods were more extensively/heavily damaged. Similar correlation between the extent of damage and the building-period-to-site-period proximity was also observed in the 1985 Mexico earthquake and more recently in Kathmandu during the 2015 Gorkha earthquake [48]. In discussion with the reconnaissance team, Mexican engineers confirmed that building-to-site period/frequency separation is an unwritten rule invariably followed by Mexican engineers after the 1985 earthquake, which appears to have contributed to the much better performance for the modern building stock in this earthquake. Hence, keeping the building period away from the local site period, particularly for deep basin environments, by controlling the stiffness of the building structural system is an effective way to design better performing buildings. A similar conclusion was drawn after the concentration of damage in 5-15 storey buildings along the Wellington waterfront during the 2016 Kailkoura Earthquake [49].

The team noticed that the sizes of columns in taller buildings were generally larger than what is provided in similar height buildings in New Zealand. On a closer scrutiny of the Mexican design approach, it was found that in soft soil zones the constant (maximum) design coefficient is extended until a very long period. Apparently, this is to cater for the site amplification around the longer period of the soft soil of the Mexican lakebed. While in NZ code, the design demand starts reducing beyond 1s (even in the softest soil type E), in Mexico the design demand remains constant (at its maximum value) until 4s for structures on soft soils. On a quick comparison between the Mexican code and NZS 1170.5 spectra (see Figure 3), a tall building with 3s natural period on soft soil (say type D) is designed for over 2 times larger design actions in Mexico City than in Wellington. The difference becomes greater for taller buildings (up to 4s natural period). Ongoing revisions to the NZS 1170.5:2004 [22] design spectra to account for the basin effects in Wellington will begin to address this disparity; however, the authors still encourage structural engineers to focus on trying to avoid designing buildings with periods close to the site period in deep basin sites as noted above.

In Mexico City, several RC frame buildings were saved from severe structural damage and collapse by masonry infill walls that were connected to RC columns. By providing additional strength and stiffness that are not directly accounted for in design, the masonry infill walls can make a flexible and weak RC frame building meet life safety performance requirement. This positive contribution of infill walls was also observed in RC buildings in Kathmandu during the 2015 Gorkha earthquake [48]. Nevertheless, these walls can be vulnerable to early damage when forced to deform during an earthquake; rendering them a liability if a low-damage performance is desired. Furthermore, in larger earthquakes, the failure of infill walls can lead to a sudden drop in stiffness and strength that can lead to a localisation of damage and potentially collapse. The team was informed by local engineers, that due to the wide spread use of stiff infills in Mexico City, it has been considered that an inexpensive approach to retrofit would be to strengthen the infill walls with Fiber Reinforced Polymer (FRP) or shotcrete to reduce the potential for failure in larger earthquakes.

In Mexico, the allowable drift limit is 1.2%, which is less than half of the drift limit allowed by New Zealand Standard [22]. This smaller drift limit naturally led to stiffer buildings with shorter periods, which seemed to have helped in two ways. Firstly, this helped keeping periods of buildings away from resonance with the (longer) periods of soft soils in Mexico City. Secondly, the buildings deformed less, causing less structural and non-structural damage. The advantages (in the form of reduced damage) of designing stiffer buildings to meet smaller design drift limits were also noted in the 2016 Kumamoto earthquake [50]. This observation further reinforces the school of thought that designing stiffer and stronger buildings is an effective way to achieve low-damage performance.

One of the things that stood out in this earthquake was the superior performance of retrofitted buildings, regardless of retrofit methodology. This is not surprising, as retrofitted buildings have been reported to have performed noticeably better in other earthquakes as well, including the 2010-11 Canterbury Earthquakes [51]. Nevertheless, in this earthquake, it was observed that even pre-1985 buildings with simple/local retrofit measures (that were unlikely to have contributed to significant increase to the overall building strength) survived the earthquake shaking with little/minimal damage. This indicates timely intervention to retrofit (even partially) old non-ductile buildings may be rewarded with significant reduction in damage repair and business interruption costs in future earthquakes.

CONCLUSIONS

The 2017 Puebla Mexico earthquake, precisely on the day of the 32nd anniversary of the 1985 Michoacán earthquake, left a bitter feeling in the heart of Mexicans. The close location of the epicentre, situated in the Morelos region less than 150 km away from the capital, led to unique ground motion characteristics throughout the city. Due to the proximity of the earthquake and because of the soft soil in Mexico City the motion was amplified in the transition and shallow soft soil zone.

The 2017 Puebla earthquake exposed the vulnerabilities of Mexico City's built environment. 77 buildings collapsed and more than 8,000 buildings experienced damage ranging from slight damage to significant structural damage necessitating demolition. Significant building damage occurred in the transition zone and the soft-soil zone with shallow depth, in contrast to the 1985 Michoacán earthquake where most of the building damage was concentrated in areas with deep soil deposits.

As with most strong earthquakes impacting urban regions, the 2017 Puebla earthquake led to extensive damage in nonductile concrete buildings. Such damage included column shear failures, punching failure of flat slabs, and beam-column joint failures. The earthquake also exposed the vulnerabilities of soft-stories and plan irregularities in several buildings. Damage to non-structural components, particularly masonry infill walls used as partitions, was also observed.

The 2017 Puebla earthquake highlighted the overall better performance of buildings retrofitted after 1985. It underlined the success of affordable retrofit solutions such as steel bracing employed to limit the overall building drift as well as strengthening and repairs with steel strapping.

History suggests that each major earthquake brought a change in the Mexico City seismic design code. Following the 2017 Puebla earthquake, it is important to take the key observations and lessons into account. An update of the code for Mexico City was released in December 2017 [28]. Authorities included guidelines for assessing existing buildings and reviewed the design spectra after the 2017 earthquake. However, the seismic zone map for Mexico City has not been updated.

The consequences of the 2017 Puebla earthquake showed that an intraplate normal-faulting earthquake can produce as much damage as one generated in the subduction zone. However, lessons learned from the 1985 Michoacán earthquake bore their fruits. Following the Puebla earthquake, the overall number of victims and collapsed building was much lower than in 1985. The development of affordable retrofit solutions, the better understanding of site effects and soil-structure interaction, and knowledge gained from the extensive seismic stations network are elements that, without a doubt, contributed to the reduction of damage and the saving of lives in Mexico. Nevertheless, each event leading to damage should be taken as an opportunity to learn and implement a new step for further improvement. The 2017 Puebla Mexico earthquake should also contribute to future progress for Mexico in the form of design of its buildings and improvement of its design code. Lessons learnt should also foster progress in other countries.

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