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FACTORS AFFECTING BUILDING DAMAGE INDUCED BY THE SEPTEMBER 2017 MEXICO EARTHQUAKES

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Abstract

On September 7 2017, at 23:49 CDT (localtime) a great earthquake struck Mexico. Its magnitude was measured M 8.2 (UNAM) or 8.1 (USGS) and its epicenter was determined offshore Chiapas and more specifically in the Gulf of Tehuantepec, almost 750 km away from the Mexico City. This earthquake caused 98 fatalities, 80% of which occurred in Oaxaca and 800000 in need of humanitarian aid in Oaxaca and Chiapas.

Twelve days after the generation of the M8.2 Chiapas earthquake, another major earthquake struck Mexico. On September 19, 2017, at 13:14 CDT (localtime) an M 7.1 earthquake struck Central Mexico. Its epicenter was determined onshore, about 55 km south of Puebla City and 130 km south of Mexico City. Unfortunately, the earthquake claimed the life of 369 people in Central Mexico due to building collapse attributed to violent and prolonged shaking, while 6011 were injured due to falling debris. Heavy structural damage was induced in the Greater Mexico City area and in the Mexican states of Puebla and Morelos resulting in 228 fatalities.

The authors conducted a field macroseismic survey shortly after the generation of the earthquakes in order to assess the earthquake impact on the building stock in the affected area of Mexico City and the surrounding states of Puebla and Morelos. Based on this field survey, the following conclusions can be drawn:

The dominant building types in the affected areas are reinforced concrete (R/C) buildings with R/C frame and infill-partition walls, masonry structures with masonry load-bearing walls, adobe structures and mixed types.

The first earthquake caused damage to the building stock of the Chiapas and Oaxaca states in southern Mexico. All types of the aforementioned buildings suffered damage varying from negligible to slight non-structural damage comprising hair-line cracks in very few walls and fall of small pieces of plaster to heavy structural damage including total or near total collapse.

The second earthquake caused damage to the buildings of Mexico City and the states of Puebla and Morelos in Central Mexico. 40 buildings collapsed in Mexico City, while hundreds of others suffered considerable non-structural and structural damage forcing residents to evacuate.

Damage are attributed to the prevalence of the vertical component in Chiapas and Oaxaca states, the violent and prolonged shaking due to extreme amplification of seismic waves, the duration of intense ground motion within the Mexico basin, the differential settlement of the lake sediments under the earthquake loads, the building pounding, the prevalence of the horizontal component of the earthquake ground motion especially in Mexico City, the prevalence of the vertical component in the majority of the affected areas in Puebla and Morelos states.

The damage induced by the second earthquake was extremely concentrated and focused in specific areas. The damaged buildings were concrete frame structures with masonry infill, which is the dominant building type in Mexico City and especially in these constructed prior to 1985, with mid-height and 4 to 8 stories. Many of them were non-ductile structures and characterized by structural deficiencies and irregularities.

Keywords: building damage; Mexico; vertical component; horizontal component; building pounding

1. Introduction

Mexico is located in the south part of North America and from the geotectonic point of view in the east of the Central Mexico Subduction Zone, where the Cocos plate subducts under the North American Plate (Fig. 1) resulting in large subduction thrust earthquakes with moment magnitude up to Mw 8.0 every 40-60 years. Mexico is affected not only by interplate seismic events along the Central Mexico Subduction Zone, but also by intraslab earthquakes in the subducting Cocos plate, and crustal earthquakes along the Mexican volcanic belt (Fig. 1).

The interplate earthquakes rupture Cocos - North American plate interface along the Pacific coast of Mexico. The faulting occurs on a low-angle thrust plane at a relatively shallow depth of about 15-25 km. The intraslab earthquakes are generated in the Central Mexico. The faulting occurs at a depth of ~40-80 km and indicate normal faulting.

Mexico City is also affected from earthquakes having different origin. There exist four types based on [1]: (1) local earthquakes; (2) continental plate earthquakes; (3) intermediate depth earthquakes and (4) subduction earthquakes. The subduction earthquakes occur at distances of more than 300 km from the city, while the intraslab earthquakes at distances close to 150 km from the city (Fig. 1). It has been observed that the normal-faulting and subduction earthquakes are the most dangerous events for Mexico City.

A characteristic example of a subduction earthquake is the September 19, 1985 Mw 8.0 Michoacán event. It caused unprecedented damage to the building stock of Mexico City with more than 4000 buildings suffering very heavy structural damage including total or partial collapse and consequently more than 10000 human losses. Based on statistical analysis of the 1985 earthquake, it is concluded that damage distribution was not random [2; 3; 4; 5]. The distribution was strongly related to the distribution of the lacustrine sediments of the Mexico basin and the height of the damaged structures [2; 3; 4; 5]. More specifically, high-rise buildings with 7-12 storeys founded on lacustrine sediments of the affected basin suffered very heavy structural damage, in contrast to low-rise buildings that suffered lighter structural or heavy non-structural damage.

The last destructive geodynamic episodes in the evolution of Mexico occurred during September 2017 (Fig. 1). On September 7, 2017, an M 8.2 earthquake struck Southern Mexico with epicenter located offshore in Tehuantepec Gulf, almost 750 km southeast of Mexico City. On September 19, 2017, an M 7.1 earthquake struck Central Mexico with epicenter determined onshore, about 130 km south of Mexico City. This earthquake claimed the life of 370 people in Central Mexico.

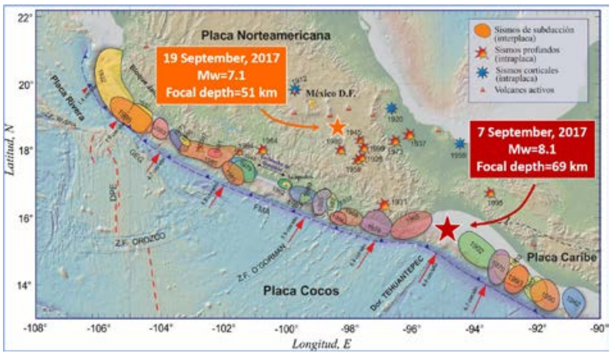


Fig. 1 – The Central Mexico Subduction Zone, where the Cocos plate subducts under the North American plate, along with interplate historical and recent earthquakes and its seismic gaps. The intraslab earthquakes within the subducting Cocos plate and the crustal earthquakes along the Mexican volcanic belt are also illustrated. The epicenters of the September 2018 Mexico earthquakes are also illustrated (modified from http://usuarios.geofisica.unam.mx/vladimir/images/EQ_map_2013_es_clear.jpg).

The aim of this paper is to present the building damage induced by the September 2017 earthquakes and observed by the authors during a field survey in the affected areas of Mexico shortly after the generation of the earthquakes. Moreover, the factors controlling building damage distribution along with the geological setting of Mexico basin and the dominant building types of the affected areas are also discussed.

2. Geological setting of Mexico basin, amplification of the seismic motion and aggravation of earthquake-induced damage

The Mexico basin is a closed, ellipsoidal basin, having a major axis measuring about 100 km from the Sierra de Pachuca to the north, to the Sierra de Chichinautzin to the south (Fig. 2). The minor axis has a length of 80 km measured from the Sierra de Las Cruces to the west, to the snow covered peaks of Iztaccihuatl on the east. The mountain ranges that bound the Mexico basin are of volcanic origin, have chemical composition from intermediate to basic and have ages that vary from Middle Oligocene to recent [6] (Fig. 2). The central part of the area consists of lacustrine soft clay deposits (Ql), which are surrounded by alluvial deposits (Qal) that also extend below the lacustrine deposits (Fig. 2). More specifically, Mexico basin is divided into three main zones: (Zone I) the Hill Zone, where tuffs dominated; (Zone II) the Transition Zone, formed by alluvial fans at the base of the hills; and (Zone III) the Lake Zone, corresponding to the soft lake beds (Fig. 2).

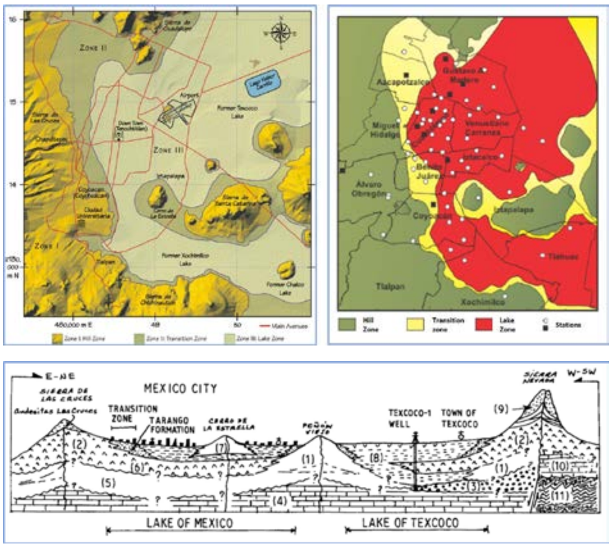


Fig. 2 – (up left) Mexico basin bounded by mountain ranges of volcanic origin and age from Middle Oligocene to recent [7]. (up right) Mexico basin is divided into three main zones (modified from [8]). (down) Schematic geologic section through Mexico basin. 1: Oligocene-Miocene; 2: Miocene-Pliocene; 3: Texcoco conglomerate; 4: Cretacic limestone; 5: Latites, dacites, andesites and basaltic andesites; 6: Tufas, lavas and pyroclastic flows, mainly of andesitic composition; 7: Tufas; 8: Lacustine sediments and evaporates; 9: Andesites and dacites from the Iztaccihuatl volcano; 10: Cretacic limestones; 11: Schists of the Acatlan group (from [9]).

The Mexico City occupies the area of the former Lake Texcoco and settlements in the Prehispanic Mexico basin (Fig. 3), where soft lake sediments occur. The negative impact of the ancient lake deposits to the buildings is that Mexico City experiences some of the largest seismic site effects worldwide. Besides the extreme amplification of seismic waves, duration of intense ground motion from large subduction earthquakes exceeds three minutes in the lake-bed zone of the basin, where hundreds of buildings collapsed or were seriously damaged during the 1985 Mw 8.0 Michoacán earthquake. Different mechanisms contribute to the long lasting motions, such as the regional dispersion and multiple-scattering of the incoming wavefield from the coast, more than 300 km away from the city [10].

By means of high performance computational modeling, [10] showed that, despite the highly dissipative basin deposits, seismic energy can propagate long distances in the deep structure of the valley, promoting also a large elongation of motion. The simulations of [10] revealed that the seismic response of the basin is dominated by surface-waves overtones, and that this mechanism increases the duration of ground motion by more than 170% and 290% of the incoming wavefield duration at 0.5 and 0.3Hz, respectively, which are two frequencies with the largest observed amplification. This conclusion contradicts what has been previously stated from observational and modeling investigations, where the basin itself has been discarded as a preponderant factor promoting long and devastating shaking in Mexico City.

Fig. 3 – Mexico basin and surrounding mountain ranges. Panoramic drone view from the Mexican Federal Highway 150D (Mexico – Puebla) [11].

3. The September 2017 M 8.2 Chiapas and M 7.1 Puebla-Morelos Earthquakes

On September 7 2017, at 23:49 CDT (local time; 04:49 on the 8th UTC) a great earthquake struck Mexico. Its magnitude was measured M 8.2 (UNAM) or 8.1 (USGS) and its epicenter was determined offshore Chiapas and more specifically in the Gulf of Tehuantepec, almost 750 km away from the Mexico City (Fig. 4). It has been largely felt in Mexico City and in Guatemala City located more than 350 and 1000 km away from the epicenter respectively.

Based on the focal mechanisms provided by several seismological organizations and observatories, the earthquake was generated by the activation of a NW-SE striking normal fault (Fig. 4). At the epicentral area, the oceanic floor of Cocos plate converges with the continental edge of the North America plate at a rate of about 76 mm/yr in a northeast direction. The Middle American Trench, located in a distance of about 100 km southwest from this earthquake epicenter, is a major subduction zone extending from Central Mexico to Costa Rica with a length of 2750 km and a maximum depth of 6670 m. It constitutes the boundary between the Rivera, Cocos, and Nazca plates on one side and the North America plate on the other.

Based on the epicenter location, the focal depth and the focal mechanism of the M 8.2 September 7, 2017 earthquake, it is concluded that this earthquake can be characterized as an intraplate seismic event within the subducting Cocos slab. The rupture surface is approximately 80 km along strike and 60 km along downdip direction, while the seismic moment release based upon this plane is 2.5e+28 dyne.cm (USGS).

This earthquake caused 98 fatalities, 80% of which occurred in Oaxaca and 800000 in need of humanitarian aid in Oaxaca and Chiapas. In Guatemala, 44000 people were affected and 5835 people were displaced based on the reports of the United Nations Office for the Coordination of Humanitarian Affairs.

As regards the earthquake environmental effects, this earthquake caused the generation of tsunami waves of 1.75 m above tide level resulting in issue of tsunami alerts for the surrounding coastal areas.

Twelve days after the generation of the M 8.2 Chiapas earthquake, another major earthquake struck Mexico. On September 19, 2017, at 13:14 CDT (local time; 18:14 UTC) an M 7.1 earthquake struck the central part of the country. Its epicenter was determined onshore, about 55 km south of Puebla City and 130 km south of Mexico City (Fig. 4). Unfortunately, the earthquake claimed the life of 370 people in Central Mexico due to building collapse attributed to violent and prolonged shaking, while 6011 were injured due to building collapse and falling debris. Very heavy structural damage and maximum intensities were observed in the Greater Mexico City area and in the Mexican states of Puebla and Morelos. As regards Mexico City, more than 40 buildings suffered heavy structural damage including total or near total collapse resulting in 228 fatalities.

Based on the focal mechanisms provided by several seismological organizations and observatories, the earthquake was resulted by normal faulting at a depth of 50 km (Fig. 4). It is also considered as an intraplate seismic event within the subducting Cocos slab.

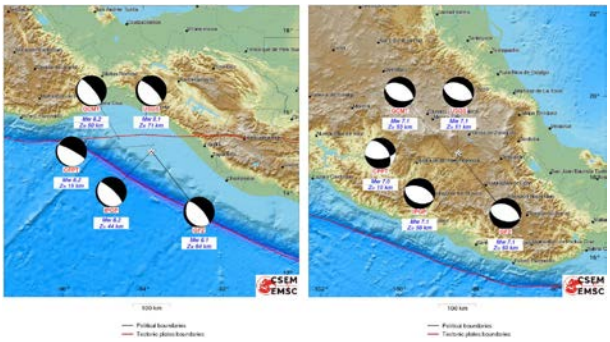


Fig. 4 – Epicenters, focal depths and focal mechanisms for the September 7 (left) and the September 19 (right) 2017 Mexico earthquakes provided by several institutes (USGS, GCMT, CPPT, IPGP, GFZ).

As far as the induced environmental effects is concerned, the earthquake triggered the eruption of the Popocatépetl volcano. The volcano burst into life sending a large plume of smoke into the sky. Based on local authorities, a church collapsed resulting in 15 fatalities in Atzitzihuacán on the slopes of the volcano. Earthquake-induced landslides were also generated in El Jale, Ixtapaluca, Mexico City. Moreover, anomalous river waves were observed in a canal of Xochimilco River close to Mexico City, which was turned into a frothing torrent as the September 19, 2017 M 7.1 earthquake hit.

The M 7.1 earthquake coincidentally occurred on the 32nd anniversary of the September 19, 1985 Mexico City earthquake that claimed the life of thousands of people and occurred as a result of thrust faulting on the plate interface between Cocos and North America plates located at a distance of 450 km to the west of the September 19 2017 earthquake epicenter. The 1985 Mexico earthquake disaster led to changes in building codes and enhanced emergency preparation measures, including the annual nationwide drills. This seismic event was commemorated and a nationwide earthquake drill was held with more than 7 million people participating, at 11 a.m. local time, just two hours before the 2017 earthquake. Millions of employees from various official entities and private companies, students from colleges and universities participated to this drill and more than 17000 buildings were successfully evacuated.

4. Dominant building types in Mexico City and the surrounding areas affected by the 2017 September earthquakes

Few days after the earthquake, members from the Faculty of Dynamic Tectonic Applied Geology of the Department of Geology and Geoenvironment of the National and Kapodistrian University of Athens visited Central Mexico in order to conduct a field macroseismic survey in the earthquake-affected areas of Mexico.

Based on field observations, it is concluded that the dominant types of buildings in the affected area of Central Mexico are: (a) R/C buildings with R/C frame and infill-partition walls (Fig. 5), (b) adobe structures (Fig. 6) and (c) mixed types of buildings. The R/C buildings constitute the majority of structures in the affected area of Mexico City and are classified into:

a) 1-6 storey buildings with R/C frame members with non-ductile detailing and unreinforced masonry plain infill of bricks, clay tiles or concrete blocks with bricks being most common,

b) 7-12 storey buildings with R/C frame members with non-ductile detailing, reinforced single diagonal strut and unreinforced masonry infill of bricks, clay tiles or concrete blocks with bricks being most common,

c) 7-12 storey buildings with R/C frame members with non-ductile detailing, supplementary reinforced elements (post and beam) and unreinforced masonry infill of bricks, clay tiles or concrete blocks with bricks being most common and

d) 7-16 storey buildings with R/C frame members with non-ductile detailing, R/C diagonal bracing and unreinforced masonry infill of bricks, clay tiles or concrete blocks with bricks being most common.

It is significant to note that many structures in Mexico City have been retrofitted and reinforced mainly after the 1985 Mexico earthquake with external steel systems (diagonal, X-, V-, inverted V- and K- bracing). These systems offer advantages such as the ability to accommodate openings and the minimal added weight of the structure. Furthermore, the minimum disruption to the full operationality of the building is obtained. Two types of bracing systems were observed: (a) the concentric bracing system and (b) eccentric bracing system.


(a)

(b)

Fig. 5 – (a) R/C buildings with non-ductile detailing with unreinforced infill walls comprising bricks, clay tiles or concrete blocks with bricks being the most common material. (b) Modern high-rise R/C buildings in Mexico City with unreinforced brick infill walls.

The masonry buildings are composed of masonry load-bearing walls that consist of bricks, clay tiles or concrete blocks. They constitute the majority of buildings in the earthquake affected Puebla and Morelos states.

The adobe structures (Fig. 6) were mainly observed in Puebla and Morelos states. Adobe (sun-dried brick) is the oldest and most common building material known to man. It is a mixture of sand, sometimes gravel, clay, water, and often straw or grass mixed together by hand, formed in wooden molds, and dried by the sun. The straw adds strength and prevents cracking.

Rammed earth (pise) is damp or moist earth, with or without an additive. It is rammed (tamped) in place between temporary moveable formworks. The best soils for rammed earth contain about 30% clay and 70% sand. The use of horizontal courses of adobe bricks prevents total detachment of rammed walls due to vertical cracks.

Foundations play an important role in the structural behavior of adobe buildings during earthquakes. Buildings with larger and stronger foundations are less vulnerable to earthquakes. Foundations are usually made of stone rubble with mud or lime mortar. To prevent water erosion, the first few courses of a wall above the foundations (plinth) are constructed using stone rubble or fired brick and lime mortar. The height of plinth should be above the flood water line or a minimum of 35 cm above ground level. After completing the plinth, masonry a damp proof course should be installed.

Massive adobe structures in Mexico are in generally good condition because natural lime plasters that helped the adobe materials breath had remained in use, rather than cement which traps moisture causing the adobe to crumble.

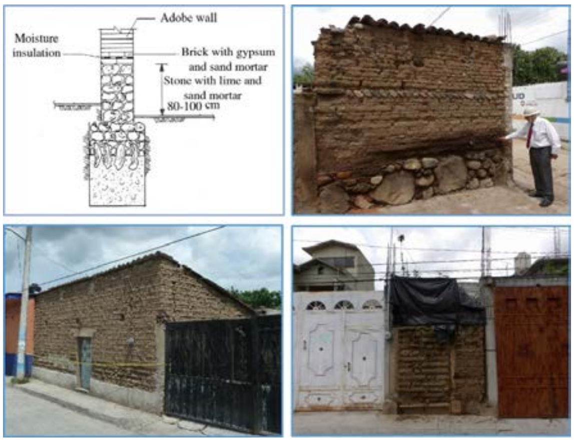


Fig. 6 – Details of the foundations of the adobe buildings (up left) and details of adobe structures that comprise the majority of buildings in Pueblas and Morelos states of Central Mexico.

5. Building Damage Due To the September 2017 Earthquakes in Mexico City and Central Mexico

Several R/C buildings with exterior non-structural damage were observed in the Oaxaca and Chiapas states induced by the first earthquake and in the Greater Mexico City area and Puebla and Morelos states induced by the second earthquake (Fig. 7, 8). This damage comprised horizontal and subhorizontal cracks in the infill walls mainly in Oaxaca and Chiapas states induced by the first earthquake and diagonal cracks in the Greater Mexico City area caused by the second earthquake (Fig. 7, 8). Moreover, detachments of plaster pieces from the infill walls, detachment of the infill walls from the surrounding R/C frame, and partial or total collapse of infill walls as well as damage to window, parapets on balconies and ornamental molding along the roof line of older buildings induced by both earthquakes (Fig. 7, 8). The generation of horizontal and subhorizontal cracks is attributed to the prevalence of the vertical component of the earthquake ground motion, while diagonal cracks are due to the prevalence of the horizontal one.

R/C buildings in Oaxaca and Chiapas states suffered very heavy structural damage from the first earthquake (Fig. 9). The common characteristic of the inspected buildings was the decomposition of the concrete in the columns of the ground floor due to crashing resulting in failure of columns and the subsequent tilting or the vertical collapse within the plan of the ground floor, while the upper floors of the structures were left practically intact. This damage is typical of an earthquake with prevalence of the vertical component of the earthquake ground motion over the limited horizontal component [12; 13]. As regards the impact on the building stock of Mexico City, there was no damage reported by the first earthquake. Only some buildings were trembled forcing residents to evacuate.

R/C buildings in the Greater Mexico City area and in Puebla and Morelos States suffered structural damage from the second earthquake ranging from light to very heavy. Immediately after the event, the Mexican government reporting to public media indicated 9722 affected buildings with 1632 of them suffering total or partial collapse, 279 schools in need of repairs and 17 hospitals in poor condition. Based on the spatial distribution of the 38 totally collapsed buildings in the city [[14]; based on data from [15]], it is concluded that they were concentrated in the western and southwestern part of the transition zone (zone II, dominant site period ~1 s) and in the lake zones (IIIa and IIIb, dominant site period ~2 s) (Fig. 10). In comparison with the distribution of damage induced by the 1985 Mw 8.0 Michoacán event, the majority of the collapses occurred in the softest lake bed sediments in the zones IIIb/IIIc (dominant site period ~2 s) [2; 3; 4; 5]. Based on the detected distribution, it is concluded that site effects must have played an important role in determining the damaged zones within the Mexico City from the September 19, 2017 earthquake.

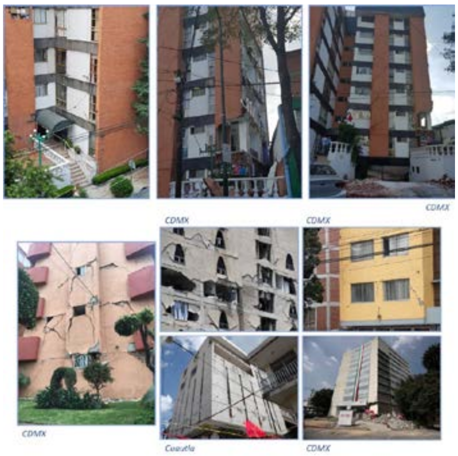


Fig. 7 – Non-structural damage in RC buildings in Mexico City (Ciudad de México: CDMX) and Cuautla (Morelos State).

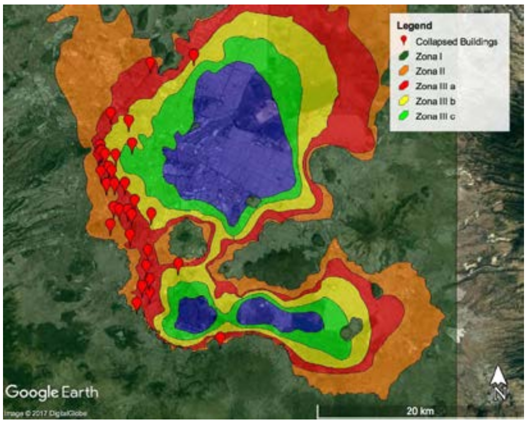
Fig. 8 – Non-structural damage to R/C and mixed type buildings in the affected area due to the September 19, 2017 M 7.1 Puebla-Morelos earthquake. Cracks in the infill walls and detachment of pieces of plaster from the infill walls.

Fig. 9 – R/C buildings in Oaxaca State with damage induced by the September 7, 2017 earthquake.

Moreover, the total collapses induced by the second September 2018 earthquake were observed in buildings that appeared to have structural deficiencies including soft stories, structural irregularities, and discontinuous or incomplete lateral load paths (Fig. 11).

The most common structural damage to the R/C buildings in the Greater Mexico City area was mainly attributed to differential settlement (Fig. 12) and the subsequent foundation movement and to building pounding (Fig. 13). Buildings affected from these phenomena were still standing after the earthquake. They either tilted due to differential settlement (Fig. 12) or suffered heavy damage due to pounding (Fig. 13).

The adobe buildings suffered non-structural and structural damage by both September 2017 earthquakes. The non-structural damage generally comprised detachment of plaster from and light cracking of the walls (Fig. 14). In Oaxaca and Chiapas states affected by the first earthquake, the structural damage to the adobe and masonry buildings comprised extended cracks in the load-bearing walls and partial or total collapse of the walls. The presence of horizontal or subhorizontal cracks in the majority of the observed structures, damage in the upper part of the structures, the symmetrical distribution of damage in the upper corners of the structures as well as the partial collapse with the still standing part left intact by the earthquake (Fig. 14) are damage indicative of the prevalence of the vertical component of the earthquake ground motion over the horizontal one [12, 13]. In Puebla and Morelos states affected by the second earthquake, similar structural damage were also observed (Fig. 15).



Zone	Number of buildings		
	Collapsed	High Risk	Security Uncertain
I	2	4	2
II	9	45	52
IIIa	15	110	58
IIIb	12	140	125
IIIc	-	36	32
IIId	-	5	1
Total	38	340	273

Fig. 10 – Collapsed buildings as included in the CICM database as of October 24, 2017 overlaid with geozones in Google Earth [[14]; based on data from [15]].

Fig. 11 – Very heavy structural damage (total collapse) of buildings in the Greater Mexico City area induced by the second earthquake in September 2018.

Fig. 12 – Tilting of buildings in Mexico City due to the September 19, 2017 earthquake and the related differential displacement affecting the building foundation. The structural components of the building were generally undamaged.

Fig. 13 – Damage induced by pounding between closely spaced buildings due to the September 19, 2017 earthquake.

Fig. 14 – Non-structural and structural damage induced by the first earthquake on September 7, 2017 to the adobe and masonry buildings in Oaxaca and Chiapas states.

Fig. 15 – Non-structural and structural damage induced by the second earthquake on September 19, 2017 to the adobe and masonry buildings in Puebla and Morelos states.

6. Conclusions

Based on the field survey conducted by the authors in the September 2017 earthquake-affected areas of Mexico City and the Chiapas, Oaxaca, Puebla and Morelos states, the following conclusions can be drawn:

The September 7, 2017 M 8.2 Chiapas earthquake caused damage to the building stock of the Chiapas and Oaxaca states in southern Mexico. All types of the aforementioned buildings suffered damage varying from negligible to slight non-structural damage comprising hair-line cracks in very few walls and fall of small pieces of plaster to heavy structural damage including total or near total collapse.

The September 19, 2017 M 7.1 Puebla-Morelos earthquake caused damage to the buildings of Mexico City and the states of Puebla and Morelos in Central Mexico. 38 buildings collapsed in Mexico City, while hundreds of others suffered considerable non-structural and structural damage forcing residents to evacuate.

Damage are attributed to the prevalence of the vertical component in Chiapas and Oaxaca states, the violent and prolonged shaking due to extreme amplification of seismic waves, the duration of intense ground motion within the Mexico basin, the differential settlement of the lake sediments under the earthquake loads, the building pounding, the prevalence of the horizontal component of the earthquake ground motion especially in Mexico City, the prevalence of the vertical component in the majority of the affected areas in Puebla and Morelos states.

The damage induced by the second earthquake was extremely concentrated and focused in specific areas. The damaged buildings were concrete frame structures with masonry infill, which is the dominant building type in Mexico City and especially in these constructed prior to 1985, with mid-height and 4 to 8 stories. Many of them were non-ductile structures and characterized by structural deficiencies and irregularities.

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