

Reconnaissance of the 2017 Central Mexico Earthquake

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Key Facts

- Hazard Type: Earthquake
- Date of the disaster: September 19th, 2017
- Location of the survey: Mexico City, Puebla, Morelos
- Date of the field survey: October 15th to 19th, 2017
- Survey tools: Microtremor
- Key findings: site effects, contribution of sinking to the amplification of damage, need for implementation of mandatory retrofitting of old structures and seismic revision of damaged structures

Key Words: *site reconnaissance, building damage, ground failure, Mexico Earthquake, Puebla Earthquake*

1. INTRODUCTION

On September 19, 2017, 13:14 local time, an intraplate earthquake ($M_w=7.1$) was registered at the state limit of Puebla and Morelos, in the central part of Mexico. The epicenter (18.40N and 98.72W) was located 120 km away from Mexico City and 90 km away from Puebla City, at a depth of 57 km (Fig. 1). The maximum peak ground acceleration registered by the Institute of Engineering of the National Autonomous University of Mexico, was 170 cm/s^2 , 109 km away from the epicenter¹⁾. The earthquake caused 369 casualties and affected Mexico City and the states of Puebla, Morelos, Guerrero, Hidalgo, Tlaxcala and State of Mexico²⁾. In Mexico City, 2273 houses had total damage and 3492 partial damage³⁾. This earthquake occurred exactly 32 years after the

1985 Michoacan Earthquake that hit the Pacific Coast of Mexico City and caused at least 40,000 casualties and around 3.5 billion dollars in damage.

A brief reconnaissance was carried out from October 15th to 19th 2017 with the main focus of observing building and geotechnical damage. A map of the sites visited is displayed in Figures 1 and 2. The areas of interest were the districts of Centro, Condesa, Roma, and Villa Coapa, and the counties of Xochimilco and Tlahuac in Mexico City; Tlayacapan and Cuernavaca in the state of Morelos; and Puebla City in the state of Puebla. This paper will introduce a brief background on the geological and soil conditions of Mexico City, to understand the extent of damage during this seismic event. The results of a series of microtremor measurements on key areas, are presented to illustrate the ground motion vibration characteristics.

The affected sites observed during the visit will be discussed. Whenever relevant, pictures of the previ-

ous condition will be compared with the damage encountered.

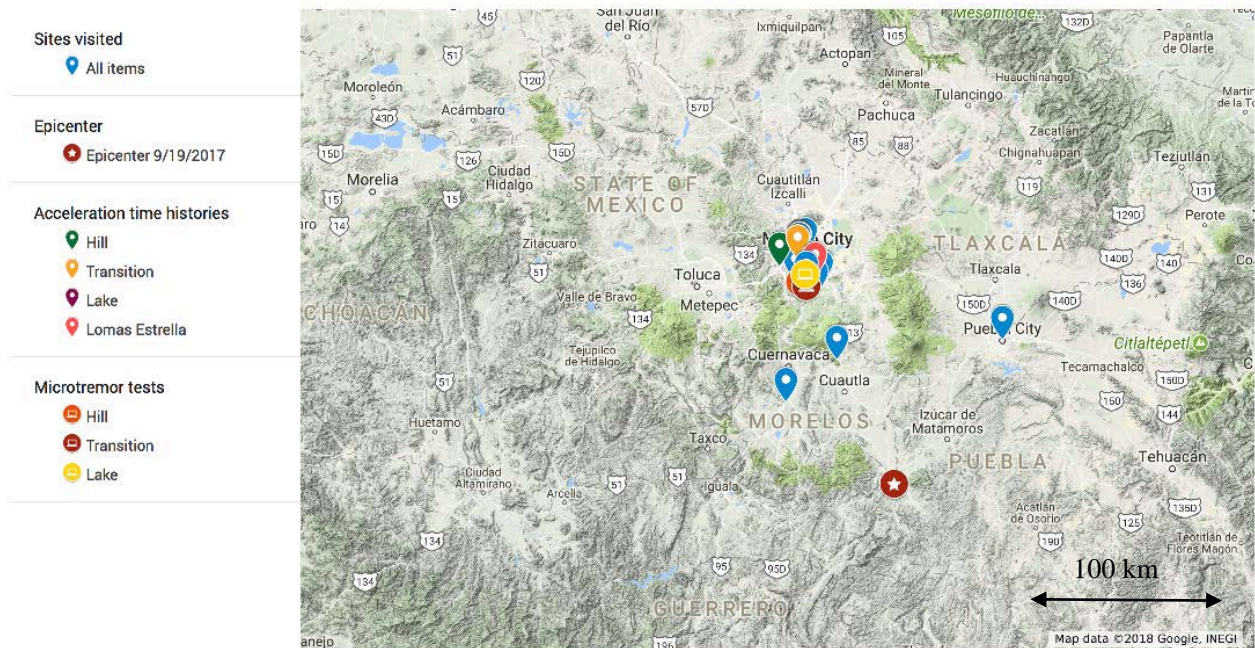


Fig. 1 Location of the epicenter and the sites visited

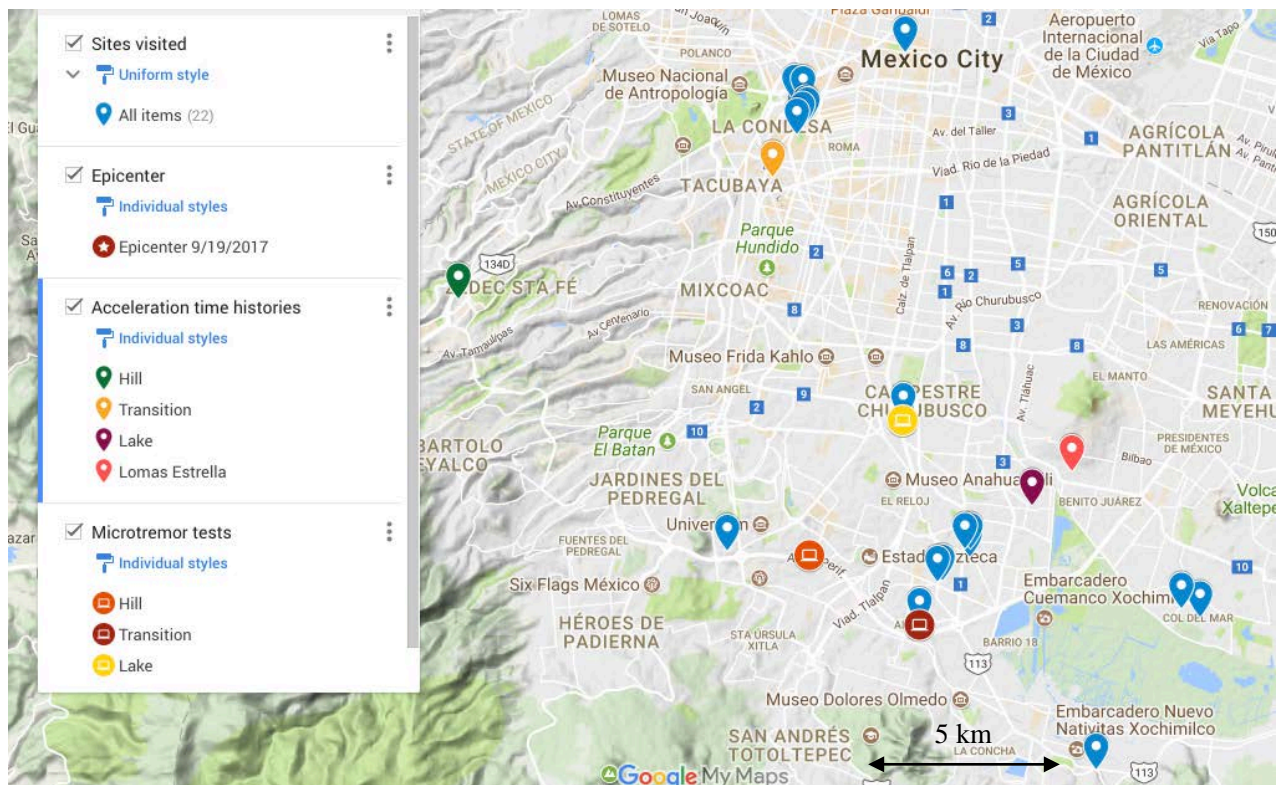


Fig. 2 Location of the seismic stations and points of microtremor tests in Mexico City

2. GEOLOGICAL SETTING OF MEXICO CITY

Mexico City is located on the subduction region of

the Cocos and the North American Plates. The Basin of Mexico, that comprises Mexico City and a part of the State of Mexico, started as a subduction zone at

the beginning of the Miocene, then turned into a valley when the volcanic activity blocked the west and east sides, and finally, became a lacustrine basin at the end of the Pleistocene, when it was surrounded by mountain ranges that stopped the drainage of the basin. Lakes started forming in the depressions during the rainy seasons and evaporated during the droughts, which originated the accumulation of sand, silt, clay, ash and alluvial clastic deposits. When the first human settlements started, there were five lakes: Zumpango, Xaltocan, Texcoco, Xochimilco and Chalco⁴. Eventually, these lakes dried out as urban settlements grew.

As a result of the climate changes and volcanic activity, the Basin of Mexico is composed of volcanic rocks and lacustrine sediments. The central part of the basin is filled with sandy silt, clayey silt and interbedded layers of volcanic ash or sand. In the high zones, there are basalt deposits and the Tarango formation formed by calcium carbonate-cemented sand, silt and gravel⁵ (Figure 3).

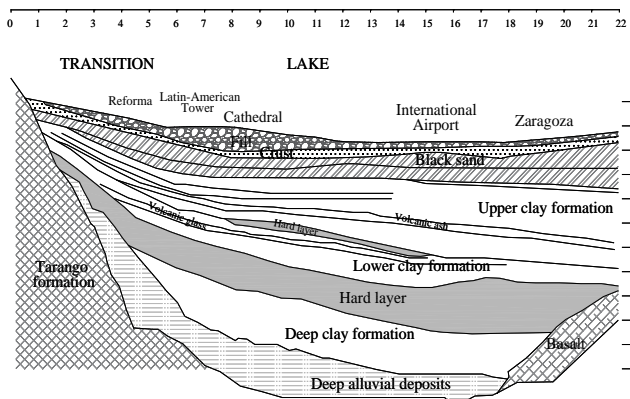


Fig.3 Soil profile in Mexico City⁶ (East-West cross section)

2.1 Seismic zoning

Due to the soil characteristics and seismicity, Mexico City was divided into three general zones by Marsal and Mazari⁵: zone I (Hill), zone II (Transition) and zone III (Lake). After the 1985 Michoacan Earthquake, the Building Code of Mexico City included went further to divide zone III (lake) into four different areas according to the variations observed in fundamental period and maximum spectral acceleration.

Zone I, also known as Hill, is formed by rocks and stiff soil with small interbedded layers of loose sand or clay.

Zone II, called Transition, is formed by sandy and silty layers, and the bedrock is usually located at 20 m depth. The seismic response of this zone shares characteristics of both Zone I and Zone III.

Zone III, also known as the Lake zone, is formed by soft soil deposits with interbedded layers of sand or silt. It is located in the central part of the Basin of Mexico, where the main lakes used to be, and in these

areas, the bedrock is located at 30 to 50 m depth.

At the west side of the city, the transition between zones is abrupt (Figure 4). During this earthquake, the damage concentrated in zones II and III, in the southwest part.

Figure 5 depicts the design spectra established by the Building Code of Mexico City for each zone.

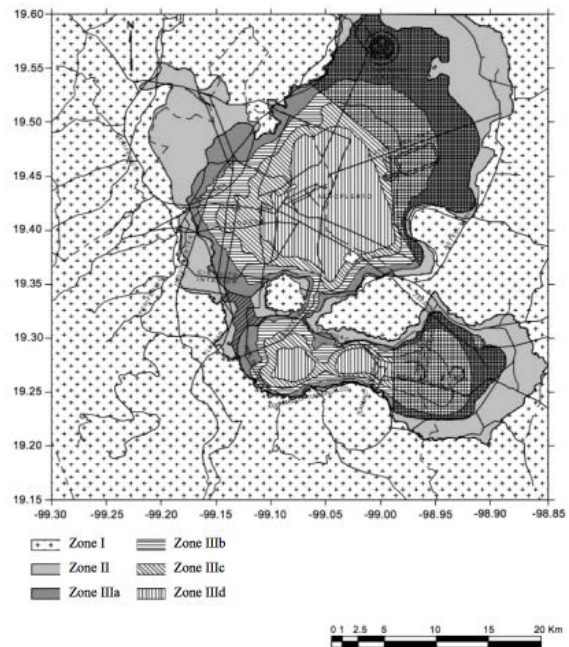


Fig.4 Seismic zonation of Mexico City⁷

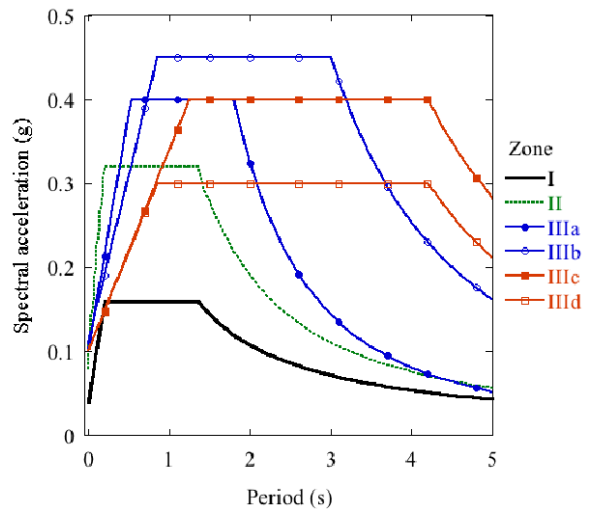


Fig.5 Design spectra for each zone⁷

3. STRONG GROUND MOTION RECORD AND MICROTREMOR MEASUREMENT

Figures 6 to 8 show the seismic records obtained from the National Seismological Service, in three seismic zones and depicted as acceleration time histories in Figure 2. The frequency components are also

shown at the bottom of each figure, where the predominant frequency can be clearly appreciated. The acceleration time histories display the different characteristics of the three different stratigraphies. The maximum accelerations in each zone and direction are summarized in Table 1.

The predominant period increases from zone I to zone III. In zone III the predominant period ranges from 1.7 to 2 s, while in zone II the predominant period ranges from 0.7 to 1.1. The peak ground acceleration in zone III exceeds 100 cm/s² which is lower than the peak ground acceleration (PGA) in that area, 160 cm/s², during the 1985 Michoacan Earthquake. However, PGA in zone I was around 30 cm/s² in 1985⁸⁾, which means that the value during the Central Mexico Earthquake was twice as big.

Nakamura and Sato⁹⁾ reported that the use of microtremor can be very effective to properly characterize the earthquake response of ground and structures. Therefore, microtremor measurements were done in

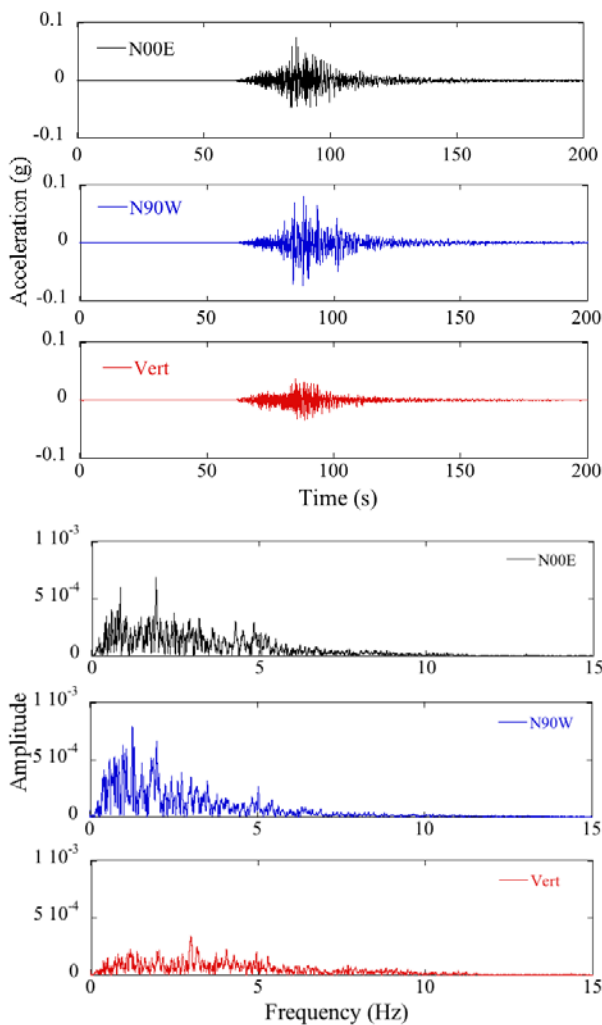


Fig.6 Acceleration time history in Zone I¹⁰⁾

spots representative of the three seismic zones, as depicted in Figure 2. Three components of ground motion (x, y, z) were recorded for 180 s using a microtremor, and three measurements were conducted at each location. Fast Fourier transform was applied to the data sets, and the three measurements were considered to smooth the frequency domain responses in the three components (s_x , s_y and s_z).

$$\text{The H/V ratio was calculated as } H/V = \frac{(s_x^2 + s_y^2)^{0.5}}{s_z}$$

The H/V ratio increases and the dominant frequency decreases from zone I to zone III (Figure 9). This is consistent with the results from Singh et al.⁸⁾

During the 1985 Michoacan Earthquake, the amplitude of the seismic waves with oscillation periods greater than 2 s was around 10 times bigger, while the amplitude of seismic waves during the Central Mexico Earthquake for oscillation periods less than 2 s, was 5 times bigger¹⁾. This had direct impacts on the damage to buildings.

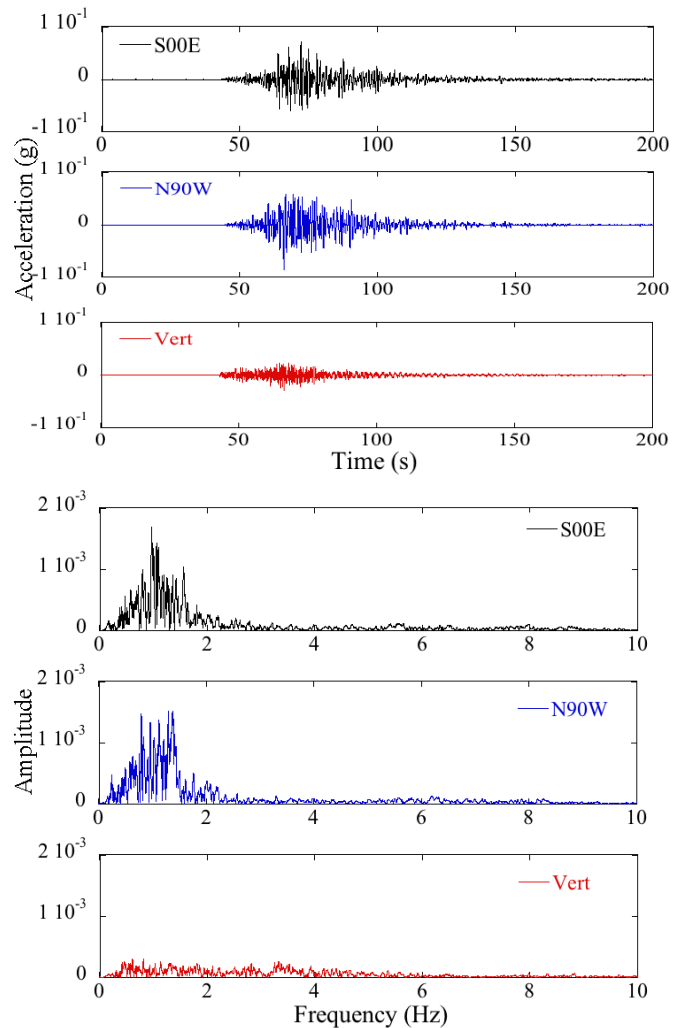


Fig.7 Acceleration time history in Zone II¹⁰⁾

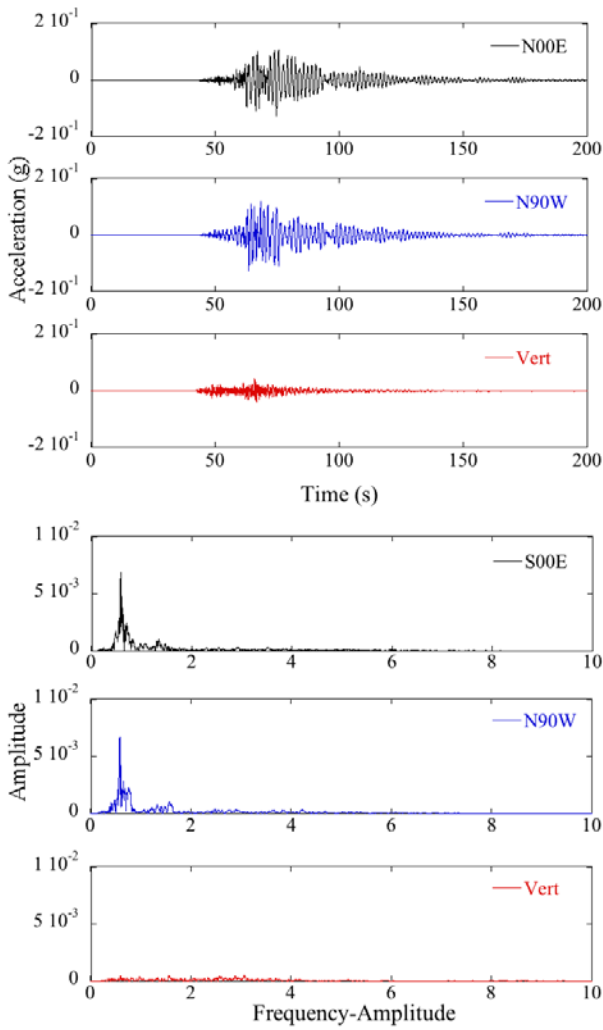


Fig.8 Acceleration time history in Zone III¹⁰⁾

Table 1. PGAs at three seismic zones

Zone	Peak ground acceleration (Gal)		
	N00E/S00E	N90W	V
I (Hill)	74.69	79.26	35.51
II (Transition)	70.49	83.91	28.19
III (Lake)	111.99	98.03	36.39

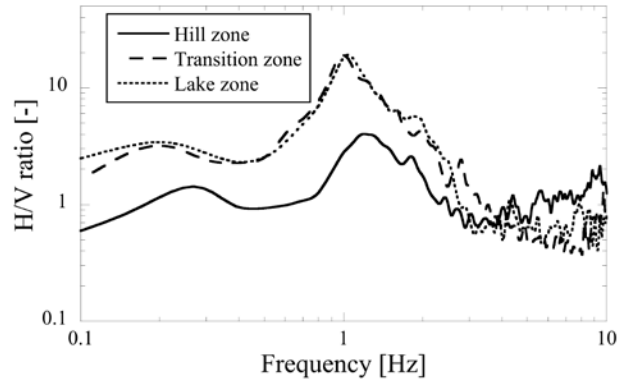


Fig.9 H/V spectrum ratio of Zones I, II and III

4. BUILDING DAMAGE

During the September 19, 2017 Central Mexico Earthquake, building damage concentrated in the central and south parts of Mexico City, especially in zones II (Transition) and IIIa (Lake). Officially, 46 buildings collapsed and a total of 5765 buildings had some level of damage³⁾. Buildings with 5 to 10 stories suffered from moderate to severe damage¹¹⁾. In Figure 10 the buildings collapsed in 2017 (red points) are overlapped on the seismic zonation, Zone II represented by the blue area and Zone III by the red area. Blue points are the collapsed buildings during the 1985 Earthquake, displayed for comparison. In the following sections, some representative examples will be described.

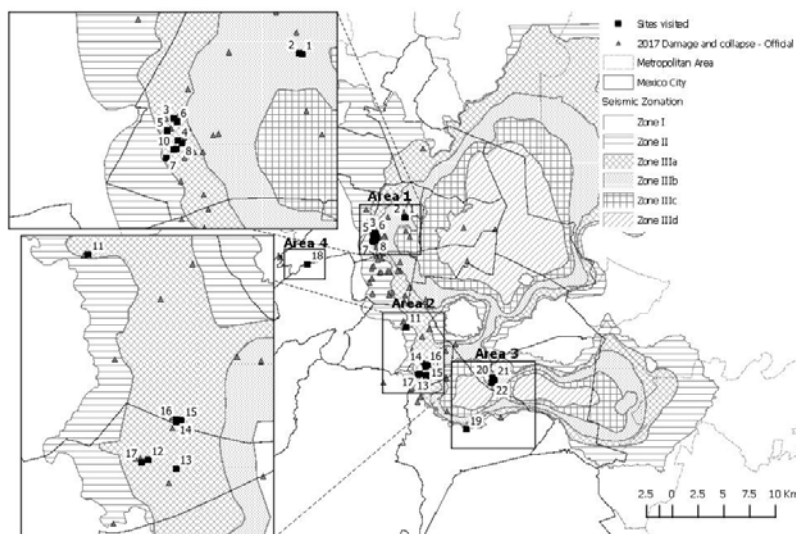


Fig. 10 Collapsed buildings of 2017 (red points) and 1985 (blue points)

4.1 Damage observed

The visit began at the districts of Centro, La Condesa and Roma Norte, that are distinguished for having thick clay layers and were severely affected during the 1985 earthquake, when around 760 buildings collapsed. The map of the studied sites is shown in Fig. 2.

Then, the districts of Coyoacan, Tlalpan and Villa Coapa, were visited to observe structural damage in the south part. In 1985, the damage concentrated in the central part, while the southern part did not exhibit significant losses. In overall, it was observed that buildings that collapsed in 1985 had longer natural periods than those that collapsed this time. Bray et al.,¹²⁾ proposed a damage index of structures that was used to classify the observed buildings (Table 2).

Table 3 is a summary of the buildings surveyed, their damage index and observations.

Table 2. Damage index of structures

Index	Description	Interpretation
D0	No observable damage	No cracking, broken glass, etc.
D1	Light damage	Cosmetic cracking, no observable distress to load-bearing structural elements
D2	Moderate damage	Cracking in load-bearing elements, but no significant displacements across these cracks
D3	Heavy damage	Cracking in load-bearing elements with significant deformations across the cracks
D4	Partial collapse	Collapse of a portion of the building in plan view (i.e., a corner or a wing of the building)
D5	Collapse	Collapse of the complete structure or loss of a floor

4.1.1 Centro

In the central district, one of the most distinguished structures was the Latin-American Tower, a 44-story building finished in 1956 (Figure 11). Its foundation consists of a combination of point bearing piles to a depth of 33 m and a reinforced concrete box at a depth of 13.5 m. The Latin-American Tower has survived the earthquakes of 1957 and 1985. During this earthquake, no damage was observed in the structure (D0).

Figure 12 shows the buildings near the Latin-American Tower which exhibited 1° of tilting. Although a previous picture (Figure 12 right) shows that these buildings have tilted before, the base of the building shows recent differential settlement (Figure 13).

Table 3. Buildings surveyed

Location	No. in Fig. 10	Damage index	Zone and comments
Latin-American Tower, Centro	1	D0	Zone III, steel frame
La Nacional, Centro	2	D2	Zone III, RC structure, corner building
Puebla 282, Roma Norte	3	D5	Zone II, 4-story, masonry and concrete, soft-story building
Alvaro Obregon 286, Roma Norte	4	D5	Zone II, 7-story, RC structure
Puebla St. and Cozumel St., Roma Norte	5	D2	Zone II, 11-story, RC structure, corner building
Cozumel 52, Roma Norte	6	D2	Zone II, 10-story, masonry and concrete, corner and soft-story building
Amsterdam 15, Condesa	7	D5	Zone II, 9-story, RC structure, corner and soft-story building
Amsterdam St., Condesa	8	D2	Zone II, 8-story, RC structure, corner building
Amsterdam St. and Cacahuamilpa St., Condesa	9	D3	Zone II, 7-story, RC structure, corner and soft-story building
Avenida Sonora 149, Condesa	10	D5	Zone II, 8-story, RC structure
Alvaro Galvez and Fuentes, Coyoacan	11	D5	Zone III, 5-story, RC structure, corner building
Elementary School "Enrique Rebsamen", Villa Coapa	12	D5	Zone III, 4-story, RC structure, corner building
Los Arcos, Villa Coapa	15	D5	Zone III, 6-story, RC structure, no adjacent buildings
Miramontes, Villa Coapa	16	D2	Zone III, 6-story, RC structure, corner building



Fig.11 Latin-American Tower, D0, Zone III

in the area were built before 1985.

Figure 14 shows a damage to 7-story reinforced concrete structure (RC) building in Alvaro Obregon 286. It was surrounded by smaller buildings and collapsed immediately after the earthquake, causing damage to the buildings on the left and the back that had to be evacuated. This issue, known as pounding, was observed in many instances after this earthquake.

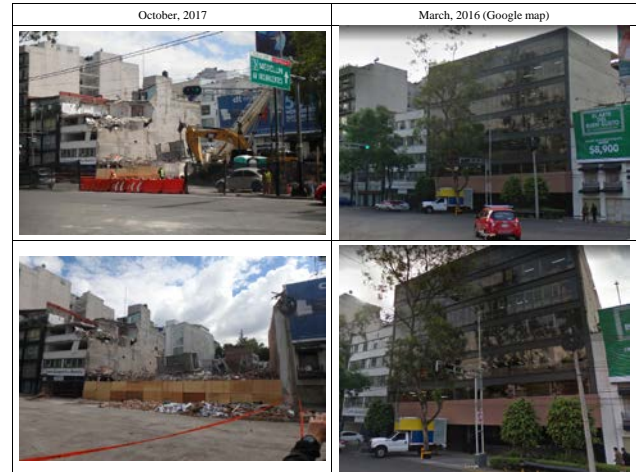


Fig.14 Alvaro Obregon 286, D5, Zone II



Fig.12 La Nacional and Sears, Centro District, D2, Zone III

Figure 15 shows a 10-story building between Puebla Street and Cozumel Street, exhibited peeling of surface and collapse of a masonry concrete block. Built before 1985, it underwent minor repair after that earthquake but it was evacuated this time. Asymmetric damage was observed due to the corner location and the 2-story house on the right side.



Fig.13 Corner of La Nacional, Centro District, D2, Zone III



Fig.15 Puebla and Cozumel Streets, D2, Zone II

4.1.2 Roma Norte

In the district of Roma Norte, several buildings of 5 to 10 stories experienced moderate damage (D2) to total collapse (D5) given that most of the structures

4.1.3 La Condesa

In this area, there were several collapses, such as the RC structure with masonry bricks in the corner of Amsterdam and Laredo Streets (Figure 16). This 9-

story building was located on the corner and had an 8-story building on the left side that suffered moderate damage (D2).



Fig.16 Amsterdam 15, D5, Zone II

A particular case was the 8-story building shown in Figure 17. This building in Avenida Sonora had the collapse of the sixth floor. It was surrounded by lower buildings on both sides. A repair mark was observed on the side of the RC structure, which could indicate previous repairs in the building. A reduction in stiffness from the fifth floor to the sixth floor could have caused the loss of the latter.

One of the main issues in the district of La Condesa, along with Roma, Narvarte and Del Valle, is that they suffered great damage after the 1985 Michoacan Earthquake and not all the buildings were properly retrofitted.



Fig.17 Avenida Sonora 149, D5, Zone II

4.1.4 Tlalpan and Coyoacan

Tlalpan and Coyoacan are two counties in the

south of Mexico City that lay on the seismic zones II and III.

A residential building in Coyoacan collapsed after the shaking. The 5-story building was on a corner surrounded by trees and only the ground floor remained (Figure 18). The direction of this building was different from the surrounding buildings in the block, that were built at the same time, before the 1985 Michoacan Earthquake.

In the county of Tlalpan, several residential and commercial buildings were damaged in the district of Villa Coapa. One of the most relevant cases was the elementary school “Enrique Rebsamen”, in which one of the 4-story buildings collapsed completely (Figure 19).

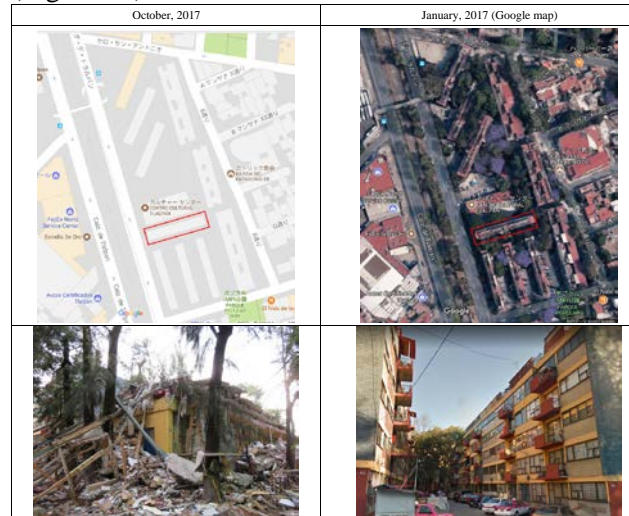


Fig.18 Residential building in Coyoacan, D5, Zone III



Fig.19 School “Enrique Rebsamen”, D5, Zone III

4.2 Overview of building damage

The collapsed buildings are displayed in Figure 20, most of them lying on Zone II and Zone III. Table 3 presents a summary of the buildings observed and the damage level.

The structural systems of damaged buildings surveyed in Mexico City, were RC structures, masonry

and concrete and steel frames. Other relevant characteristics were the location and the stiffness. Corner buildings represented 41% of all the collapsed buildings, while soft-story buildings were 57%¹¹⁾.

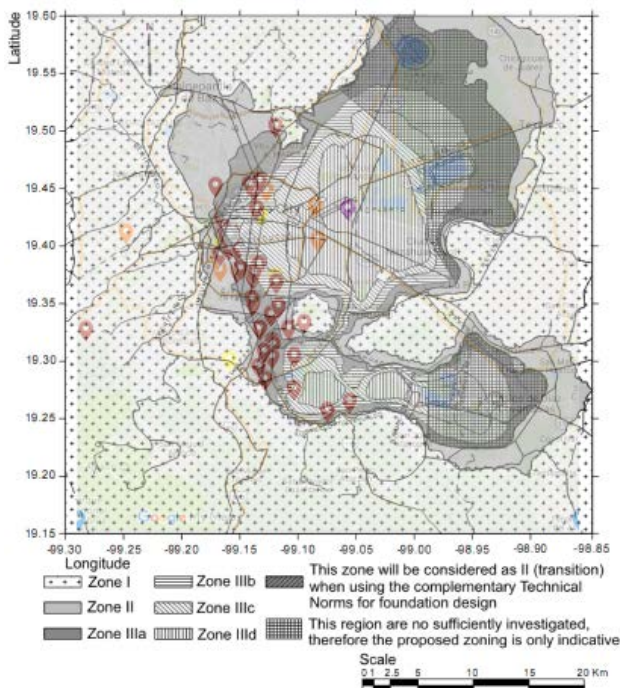


Fig.20 Seismic zonation and buildings collapsed

One of the most important observations was that most of the collapsed buildings were built before 1985 and were rehabilitated after minor repairs, for residential or commercial purposes. After the 1985 Michoacan Earthquake, the seismic evaluation of buildings that underwent minor damage was not mandatory, which made these structures more vulnerable during this earthquake.

5. GROUND FAILURE

Mexico City has experienced continuous ground subsidence since the last century. In 1890, the government started extracting water for consumption from deep wells located in the center of Mexico City. In 1925, the problem was acknowledged after measuring the settlement of the Cathedral. In 1960, the water extraction stopped in the central part but continued in the south part, in the areas of Xochimilco, Tlahuac and Iztapalapa. However, the subsidence has not ceased in the central area and has also started in the south of the city¹³⁾ (Figures 21 and 22).

This extraction has caused differential settlements and generation of cracks due to the desiccated soils, that have affected buildings, roads and historical remains. Particularly, the counties of Tlahuac and Xochimilco, that are characterized for being located in the old area of lakes and are the places where deep

wells are extracting water for Mexico City, showed great damage due to ground failure¹⁴⁾.

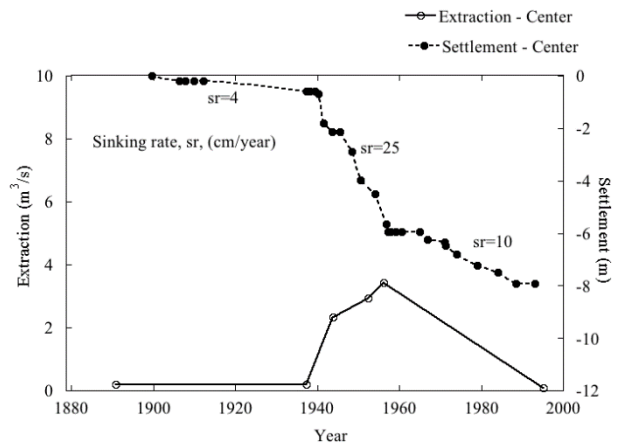


Fig.21 Subsidence in the center of Mexico City¹³⁾

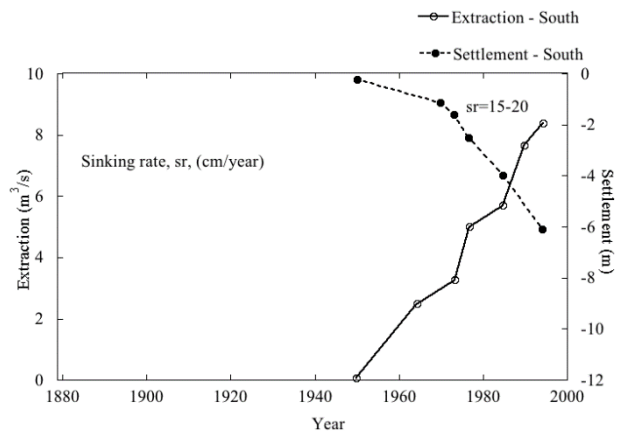


Fig.22 Subsidence in the south of Mexico City¹³⁾

5.1 Colonia del Mar

In Colonia del Mar, a district located in the region of Tlahuac, cracks have been reported since 1970. After the earthquake, the Geosciences Center of the National Autonomous University of Mexico (UNAM) released an official map of cracks in Mexico City¹⁵⁾ to deal with the reconstruction in the counties of Tlahuac, Xochimilco and Iztapalapa because during the earthquake, the existing cracks increased their extension and depth.

Site 1, in Fig. 23, is a park on the border between Tlahuac and Iztapalapa counties (Figure 24). In this area, the local government had previously built a subsidence monitoring station, that can be seen in the back, because the park had been settled for a while. However, a settlement of around 1 m was observed on the running track immediately after the earthquake, and on the date of the survey, the maximum settlement was 1.3 m.

Site 2 was a house located in Oceano St. and Pingüino St., were the pavement displaced downwards in the transverse direction of the street (Figure 25). Inside the house, along the line of the outside

crack, an existing sinkhole expanded. The sinkhole opened the year earlier but the size significantly increased after the earthquake (Figure 26).

A similar phenomenon was seen in Site 3 (Figure 27), nearby Marist University, where a sinkhole expanded, exposing the pipelines under the street. The cavities inside might indicate that a process of internal erosion have been taken place for a long time, just as in other areas of Colonia del Mar.

Along the major cracks, most of the houses were evacuated due to the risk of collapse. The houses, built of masonry and concrete, exhibited cracks, sinkholes and differential settlement. Although in this area it is recommended to have 1-story houses due to the cracks and geologic faults, several houses have two or even three stories.



Fig.24 Site 1. Settlement in a park

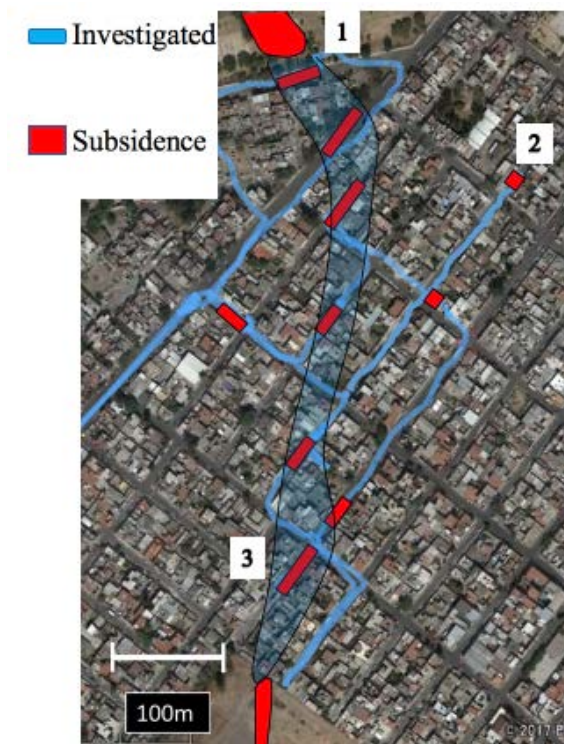


Fig.23 Area surveyed in Colonia del Mar



Fig.25 Site 2. House with a sinkhole



Fig.26 Site 2. Sinkhole inside of the house

Civil Protection carried out a survey after the earthquake and it was concluded that only in Colonia del Mar, 216 properties had low risk of collapse, 477 had medium and 340 had high risk¹⁶⁾. In Tlahuac, a total of 1240 houses is in high risk, due to the damaged caused by the earthquake and the existing cracks.



Fig.27 Sinkhole nearby Marist University

5.2 Xochimilco

In the area of Xochimilco, one lane of the Tulyehualco-Xochimilco roadway had to be closed due to the appearance of longitudinal cracks and cavities of even 1 m depth (Figure 28).

In this area of Xochimilco, houses are built on the slopes of the hill and after the earthquake, the retaining walls adjacent to the roadway leaned outwards (Figure 29). Besides, there were water outages and leakages in all the district; three weeks after the earthquake, the water service was not fully restored yet.



Fig.28 Damage in the Tulyehualco-Xochimilco highway

Transit was restricted to one lane; however, it was learnt that in the working lane a sinkhole of about 0.7 m diameter and 5.3 m depth, opened six months before the earthquake and was filled weeks later. This indicates that this district, also part of the water extracting area, is prone to cracks and cavities.



Fig.29 Inclination of retaining walls

5.3 Morelos

In the district of Piedra Grande, Tlayacapan, Morelos, the earthquake triggered a rock slide, that endangered more than 20 houses on the hill (Figure 30).

The rock mass (60 m height and 25° slope) exhibited fractures in the steeper areas. The fragments of tuff on the foot of the hill ranged from 30 to 50 cm diameter. Most of boulders (~1.5 m diameter) that slid were blocked by an older rock mass from a previous rockslide and just one hit a house in construction and perforated the wall as displayed in Figure 31. As told by the neighbors, the site has been threatened by the possible sliding of the rock mass for several years, but just after the earthquake people was told to evacuate



Fig.30 Rock mass in Tlayacapan, Morelos



Fig.31 House wall destroyed by rock falling



Fig.33 San Juan de Letrán, Puebla City

5.3 Puebla City

Puebla City is located 90 km away from the epicenter. The city has a population of about 6 million and it has more than 2000 churches and temples. It has a seismic setting due to its proximity to the Trans-Mexican Volcanic Belt.

This time, the damage concentrated in the central part and historical buildings, where 34 properties had structural issues. There were cracks and cosmetic damage in the dome of the tabernacle at the Cathedral (Figure 32).

The church of San Juan de Letran had structural damage and was closed. The structure of masonry tilted and was supported by wooden beams (Figure 33).

Besides the historical and religious buildings, new buildings experienced cosmetic damage and cracking. Structures such as the High Towers in Lomas de Angelopolis were built after the 1999 Tehuacan Earthquake and exhibited damage in the roof and the façade (Figure 34).



Fig.34 Plaza Sonata. Photo by Pilar García Téllez.



Fig.32 Cathedral in Puebla City

6. CONCLUSIONS

The September 19, 2017 Central Mexico Earthquake affected all the surrounding states but caused significant damage in Mexico City, where the site conditions and basin characteristics amplified the ground motion. Most of the structural damage concentrated in zones II and III where the previous 1985 Earthquake have also caused numerous collapses. Due to the characteristics of the ground motion, 5 to 10-story buildings were the most affected in the west side of Mexico City where the soft deposits have thickness of 10 to 30 m (zone II and zone III). There were significant factors shared by the collapsed buildings, most of them were built before the 1985 Michoacan Earthquake, and they were corner and

soft-story buildings. This pattern of damage is similar to that experienced in 1985. It is expected that the building code reinforces the need for seismic revisions and retrofitting to all the structures that underwent damage during this earthquake to prevent future damages.

In the south part of Mexico City, the earthquake worsened the existing problems. In both Tlahuac and Xochimilco, the phenomenon of subsidence have affected the ground generating cracks and sinkholes which opened or expanded during this earthquake. The recovery of this area will be very complex, as the previous subsidence conditions and the problem of water extraction need to be addressed, in addition to the earthquake damage. Regarding other geotechnical issues, there was no liquefaction and few cases of slope failure.

Other states of Mexico were also severely affected and in some cases, it will be necessary to relocate people to reduce the risk of future seismic events.

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