REPORT

Of the Post-seismic Mission on the Mexico earthquake of September 19th, 2017

Association Française du Génie Parasismique
French Association for Earthquake Engineering

February 2018

Cover photo :
Mexico, modernization and reinforcement
of the Economic Affairs tower

CDMX : Mexico City logo 2017: Centenary of the Mexican Constitution

Contents

0 Introduction

At 07:17 on September 19th 1985, Mexico City was struck by a very strong earthquake which caused massive damage and the loss of 10,000 lives.

At the time, the AFPS (French Association for Earthquake Engineering) sent a mission, composed of Victor Davidovici, Christian Duretz, Bernard Etchepare, Alain Pecker and Pierre Sollogoub, to the affected area.

The information gathered in course of this mission was significant and, consequently, the French anti-seismic regulations were modified, as were those of most countries exposed to seismic risks: The AFPS 92 recommendations and then the PS 92 regulations replaced the PS 69 regulations that had been in place since 1969.

Since then, the Mexico City earthquake of 1985 has become a landmark and a reference for the earthquake engineering community

When, 32 years later to the day, on September 19th 2017 at 13h34, a major earthquake once more struck Mexico City and media images reported extensive destruction, it did not take long before the AFPS decided to send a new mission with the objective of answering four main questions:

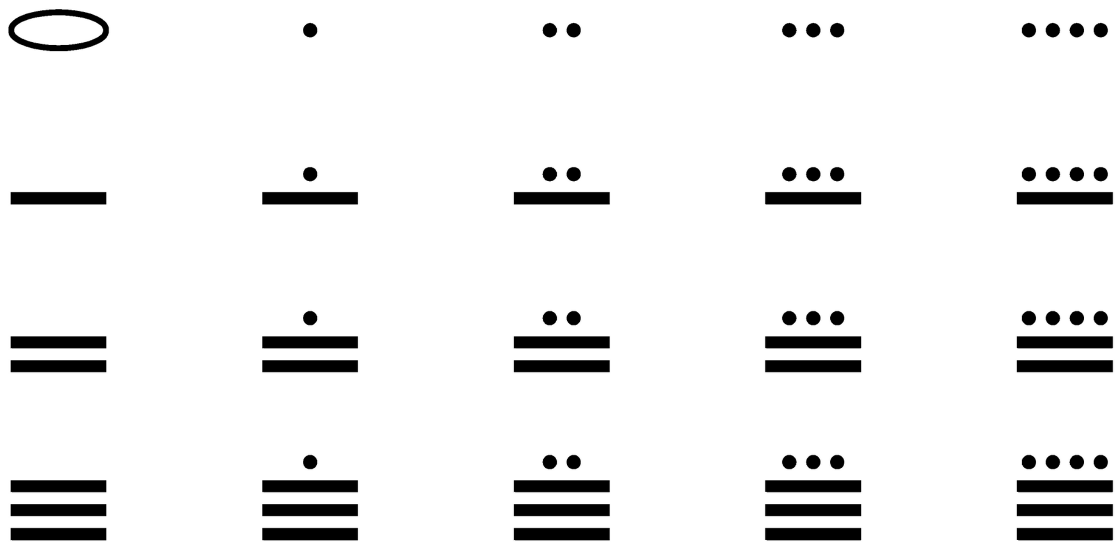
- What was the impact of the 2017 earthquake on Mexico City compared to that of 1985?
- Did the more recent buildings, constructed after 1985, behave adequately?
- Did buildings retro-fitted since 1985 behave adequately?
- How did French buildings in Mexico City, rebuilt or strengthened since 1985, behave?

The present report, with its eighty pages organized into twenty sections, attempts to answer these questions[1].

It also endeavors to expose the wide variety of issues examined in the course of the mission.

Comparable in size to the report produced by the AFPS in the wake of the 1985 event, this report is deliberately concise and synthetic. It aims to be accessible to a wider public that is not necessarily aware of all the issues associated with seismic risks. For the benefit of experts, it will be augmented by several appendices made available on the AFPS website (www.afps-seisme.org).

Figure 0.1 – The first twenty digits (from 0 to 19) in the Maya script



[1] *The Romans used a decimal numeral system (base 10). The Celts, like the Mayas, counted using a vigesimal system (base 20).In the Middle Ages in France the vigesimal system was more commonly used than the decimal one. People said "twenty and ten" for thirty, "two twenty and ten" for fifty... and "four twenty" (quatre-vingts in French) continues to be used to denote eighty in France up to the present day, instead of "huitante" or "octante" which are encountered in other parts of the French-speaking realm.*

1 Mission description

1.1 Objectives

1- Seismic hazard and Geotechnical engineering: The study will include an analysis of the regional seismotectonic context and of the mechanism associated with the event under scrutiny. A summary of all in-situ measurements (accelerometer networks, GPS, Satellites, etc.) and observations will be compiled. Local "site impacts" will also be analyzed using information collected during this mission;

2- Structure behavior: the behavior of various structures, be they of reinforced concrete-, steel frame-, or masonry construction, will be examined as will civil engineering works and buried and open air networks. These observations will be synthesized and specific textbook cases identified in order to form the subject of targeted case studies following the mission. Particular attention will be given to strengthening techniques and the behavior of structures that had been strengthened prior to the earthquake;

3- Emergency, crisis management: A feedback analysis of the emergency assessment procedures and tools implemented in Mexico will be conducted with a view to improving the protocols existing in France (works of the AFPS Emergency cell for Civil Protection);

4- Reconstruction/reconfiguration: Feedback regarding territorial reconstruction/reconfiguration following the 1985 Mexico City earthquake (anti-seismic regulations and urban planning) will be gathered in the course of visits to locations hit by this earthquake.

Apart from these four axes, which constitute the basics of all post-seismic observation missions conducted under the auspices of the AFPS, the mission was also free to consider other issues, particularly since this was the first time in AFPS history that such a mission was headed by an architect.

The team, therefore, assigned itself additional objectives concerned with the issues of architecture, historic buildings, French buildings in Mexico City, prevention, warning exercises and geographical information systems, which is certainly a very promising sector.

In addition, and as is the case for all AFPS missions, one of the main objectives was the training of the association's newer members. When it comes to training in earthquake engineering, nothing is better than experiencing the effects of an earthquake first-hand.

1.2 Team composition

The team that travelled to Mexico City was formed of eight members, listed below in alphabetical order :

Name	Affiliation	Topics
Stéphane BRULE	MENARD	Hazards, Geotechnics
Cédric DESPREZ	IFSTTAR	Structures, Emergency
Charles FERNANDEZ	GRTgaz	Structures, Geotechnics, Networks
Marc GIVRY	Marc Givry Architecte	Mission leader, Architecture, Town Planning, Emergency
Kevin MANCHUEL	EDF	Hazards and site impacts
Gustavo MENDOZA	Géodynamique & Structure Structures	Structures
Benjamin RICHARD	CEA Saclay	Structures
Carlos TAYLOR	Bureau d'Études Structures TAYLOR	Structures

Agathe ROULE from the BRGM (French Geological Survey) assisted the mission remotely by providing advice and instructions [2].

On location, Carlos CARAMES and Javier IBANEZ, from DYNAMIS ASSOCIATES, who were in Mexico City during the days following the earthquake, were able to join the mission on several occasions.

[2] *Agathe ROULE spent two years at the UNAM in Mexico City and presented a thesis in seismology on the Study of seismic movements in the valley of Mexico in 2004. The team regrets that she was unable to join the mission on location due to professional engagements. Her remote contribution, however, was invaluable.*

1.3 Mission progress

The mission took place on location over a period of 10 days and progressed as follows :

Day	Date	Team	Actions
1	07-11-2017	All	- Arrival in Mexico City, transfer to the hotel, meeting with the local support team - Mission briefing
2	08-11-2017	Team 1	- Meeting with Pr. Mario Ordaz (UNAM)
		Team 2	- Conference on the seismic events of September 1985 and 2017
		All	- Visit to the UNAM - Visit to the Seismic instrumentation Laboratory - Visit to the Earthquake Engineering Department (Dr. Raquel Garcia Benitez) - Visit to the National Disaster Center and to the Structural Testing Laboratory - Meeting with Pr. Gabriel Auvinet (UNAM) – seismological and geological context of Mexico City – foundation systems
3	09-11-2017	Team 1	- H/V measurement campaign - Meeting with Pr. Ovando-Shelley (UNAM) – discussions regarding the geotechnical context of Mexico City
		Team 2	- Visit to the sites most seriously impacted by the 1985 earthquake
		Team 3	- Visit to the BalOndeo Company (water networks) – visit to a manager of the natural gas transport network (ENGIE Mexico, Antoine Olivier)) – Meeting with Pr. Efrain Ovando-Shelley
4	10-11-2017	Team 1	- H/V measurement campaign
		Team 2	- Meeting with Pr. Meli and Pr. Ramirez at the UNAM – Evolution of codes and standards in the City of Mexico – Instrument-fitted constructions
		Team 3	- Meeting at the embassy with the management services officer and the attachés in charge of internal security - Meeting with the director of the Casa del Arquitecto
		Team 4	- Visit to the National Natural Gas Management Center (CENAGAS)
5	11-11-2017	Team 1	- H/V measurement campaign - Meeting with local representatives of the Menard company
		Team 2	- Visit to the sites most seriously impacted by the 2017 earthquake
6	12-11-2017	Team 1	- Debriefing of information collected and initial structuring of the report
		Team 2	- H/V measurement campaign
7	13-11-2017	Team 1	- H/V measurement campaign - Meeting with representatives of the Menard Company involved in the construction of the new Mexico City airport
		Team 2	- Visit to the city of Puebla (epicenter zone) - Meeting with the curator of historical monuments for the state of Puebla - Meeting with Civil Protection director for the city of Puebla - Meeting with Victor Jimenez, ENGIE Mexico (ENGIE Mexico) - Meeting with Gas de Morelos
8	14-11-2017	Team 1	- H/V measurement campaign
		Team 2	- Meeting with the local AFP director and an independent French journalist
		Team 3	- Visit to the "Instituto Francés de America Latina" and "la Casa de Francia" - Meeting with the National coordinator for historic monuments
		Departure of three of the team members	
9	15-11-2017	Team 1	- Visit to a landslide site in Cuernavaca + diagnostic visit with Pr. Efrain Ovando Shelley
		Team 2	- Meeting with the chargés d'affaires for scientific cooperation at the embassy - Meeting with the deputy Consul, Head of the Chancellery - Technical visit to the embassy - Visit to damaged historic monuments of Mexico City
10	16-11-2017	Team 1	- Meeting with the deputy director of the French Development Agency
		Departure of the remaining team members	

Figure 1.1 – GPS tracking of the mission movements between Mexico City and Puebla

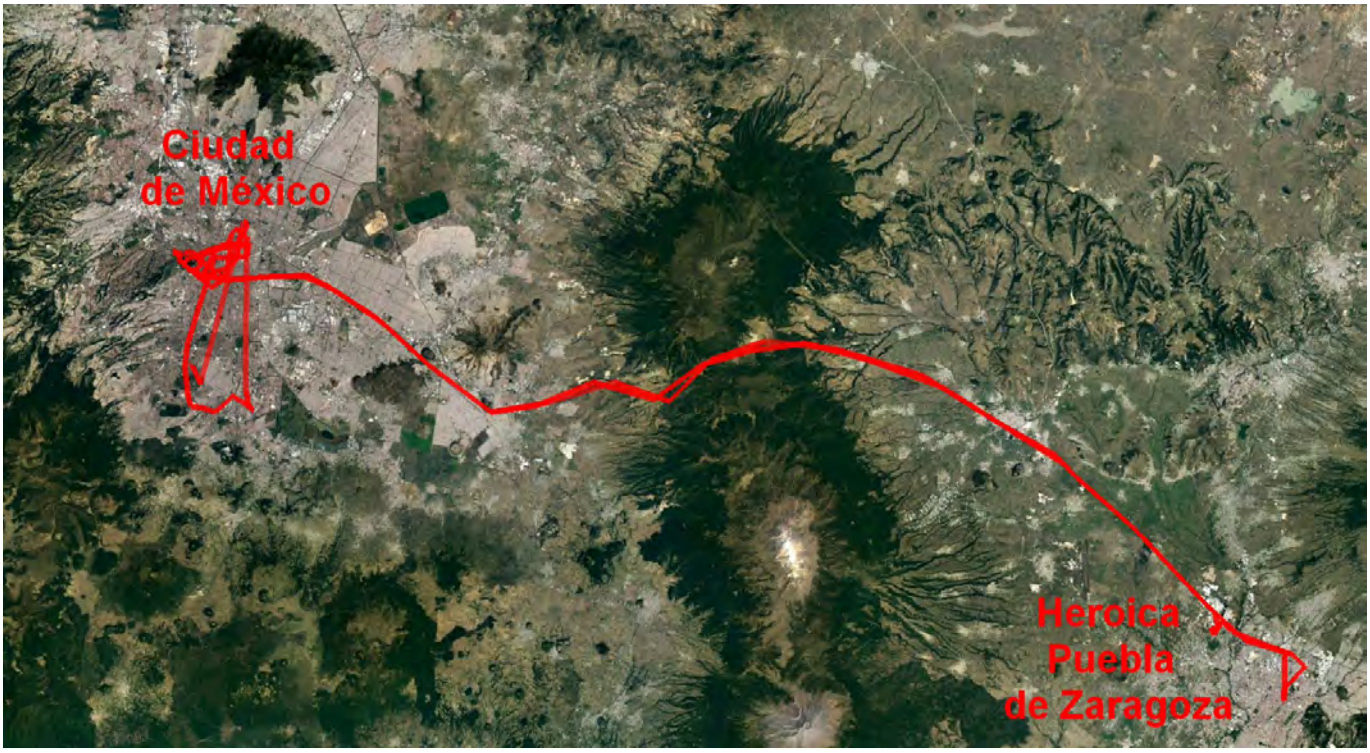


Figure 1.2 – GPS tracking of the mission movements in Mexico City

2 Seismology

2.1 Tectonic context

Mexico is located within one of the most active seismic regions on the planet. This is due to its position at the interface between five tectonic plates (Figure 2-1): the Cocos plate, the North-American plate, the Pacific plate, the Caribbean plate and the Rivera plate. A significant part of the seismic activity affecting Mexico originates from the subduction zone in an area south of the country, where the Cocos plate moves under the North-American plate at a rate of approximately 6 cm/year (Figure 2-2).

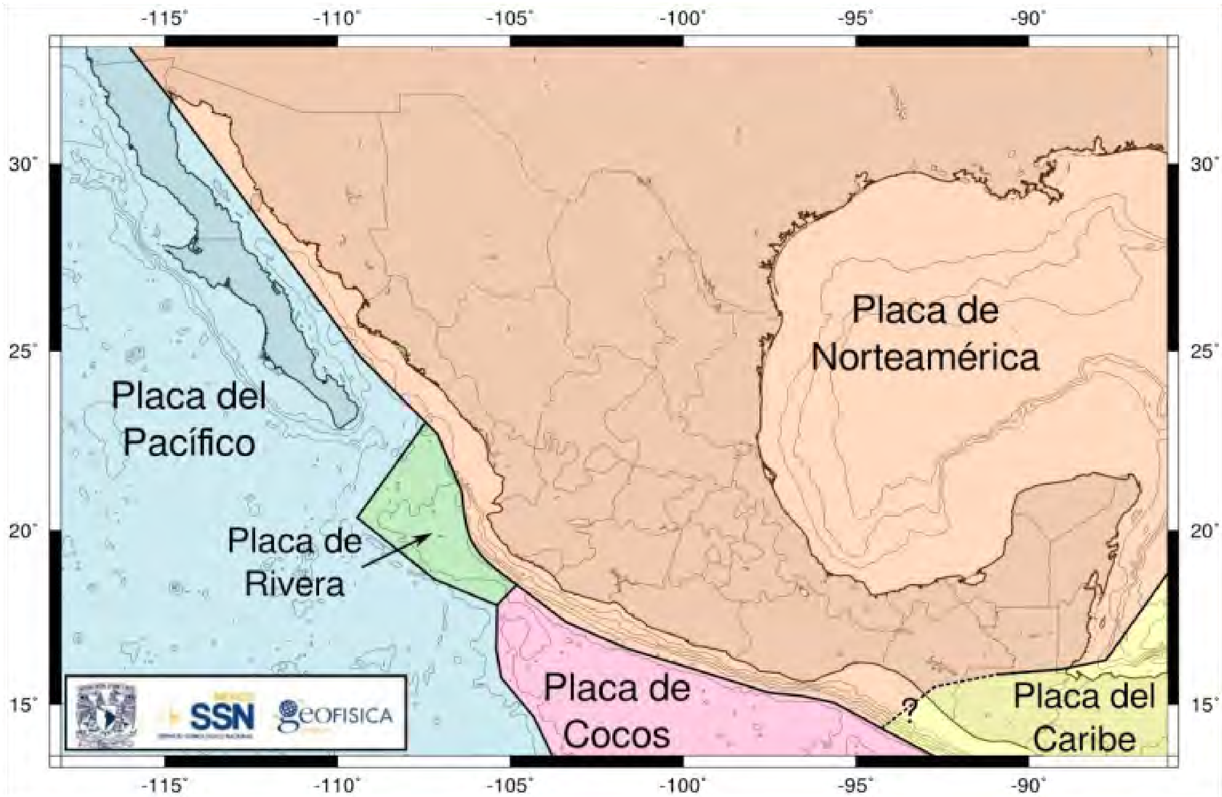


Figure 2–1 - Lithospheric plates constituting Mexico's tectonic context [1]

Within a subduction zone, the nature of earthquakes varies depending on where they actually take place. We can distinguish between:

- Interplate earthquakes, which occur at the interface or contact zone between the upper- and the subducting plate. These earthquakes exhibit what is termed a reverse fault mechanism. The locations of the major interplate earthquakes recorded since the beginning of the 20th Century are indicated by the colored areas on Figure 2-2;
- Intraplate earthquakes, which occur within the sinking plate. They proceed according to normal fault mechanisms triggered by the fact that this plate, as it sinks into the mantle, becomes stretched under its own weight. The main intraplate earthquakes recorded in Mexico feature as red and yellow stars on Figure 2-2;
- Continental earthquakes, which are located in the upper plate. They proceed according to various mechanisms (reverse-, normal- or strike-slip fault) and are triggered by stress conveyed into the upper plate through coupling with the sinking plate. The more significant examples feature as blue stars on the map in Figure 2-2.

The earthquake of September 19th 2017 was an intraplate earthquake (Mw=7.1). The location of its epicenter is displayed in Figure 2-2 and its depth is indicated in the schematic cross-section of the subduction zone below Mexico City displayed in Figure 2-3, where one can see the Cocos plate (in purple) subducting beneath the North-American plate (in yellow). In this part of the subduction zone, the Cocos plate, after it subducts under the North-American plate, remains horizontal over approximately 200 km before plunging completely into the mantle. The September 19th 2017 earthquake took place within the sinking plate, at the flexure between the horizontal part and the portion that plunges into the mantle, where extension occurs and consequently where normal fault earthquakes occur.

Throughout the 20th century, in the area where the September 19th 2017 earthquake struck, several other intraplate earthquakes have been recorded at depths which varied significantly [2]. Most notable were the earthquakes recorded on 03/02/1911 (Ms= 7.2), on 10/02/1928 (Ms= 7.7), on 15/01/1931 (Ms= 7.8), on 26/07/1937 (Ms= 7.2), on 28/08/1973 (Ms=7.3), on 10/10/1980 (Mw= 7.1) and on 30/09/1999 (Mw= 7.4). And finally, the September 7th 2017 earthquake (Mw= 8.2), which occurred further south in the Tehuantepec area, was also an intraplate event.

A major subduction earthquake struck the Michoacan State region of Mexico on September 19th 1985 (also of note was the earthquake of 28/07/1957, Ms=7.5, which caused the Angel of Independence to fall from the top of the famous victory column in Mexico City). Regarding continental earthquakes, the Acambay earthquake of 1912 is worthy of mention [3].

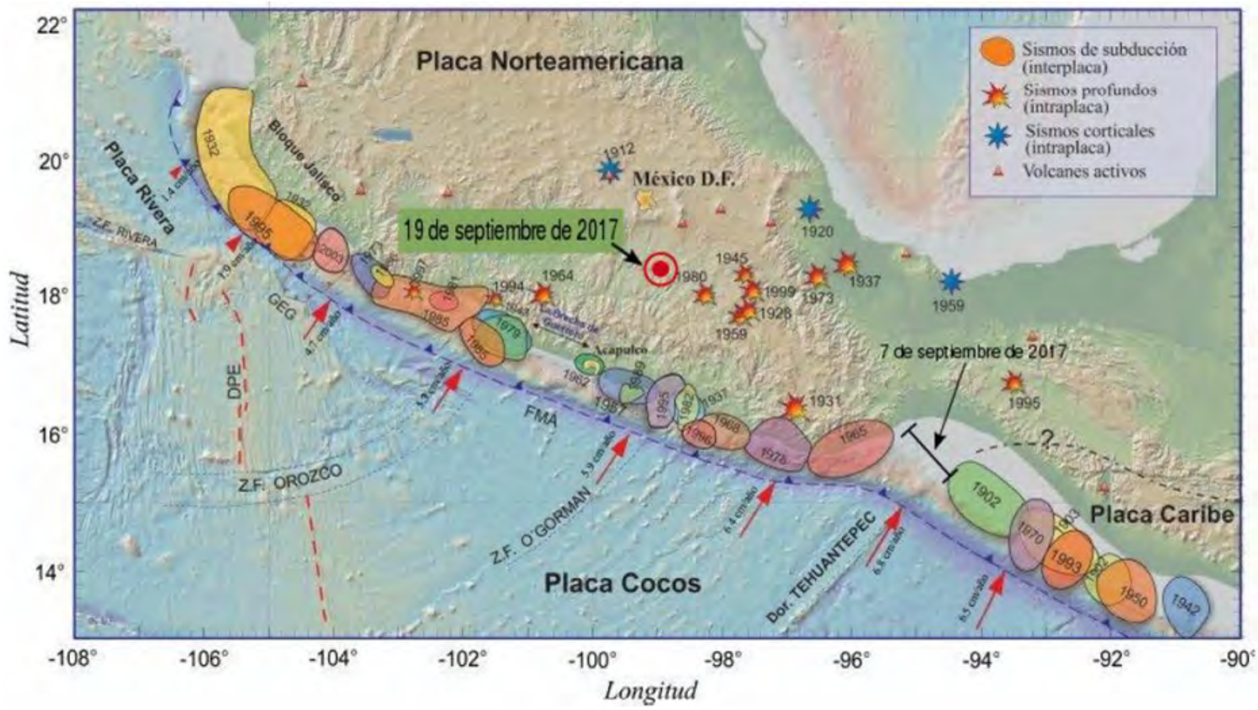


Figure 2–2 - Locations of major earthquakes recorded in Mexico [4]. The colored zones correspond to the rupture areas of interplate earthquakes, the red stars to intraplate earthquakes and the blue stars to continental earthquakes. The red bull's-eye pinpoints the epicenter of the September 19th 2017 earthquake. The line associated with the September 7th 2017 event depicts the rupture area of this earthquake, which was identified from the aftershocks. The epicenter itself is situated at the south-east end of that line. The red arrows indicate the direction of the convergence movement between the Cocos and the North-American plates.

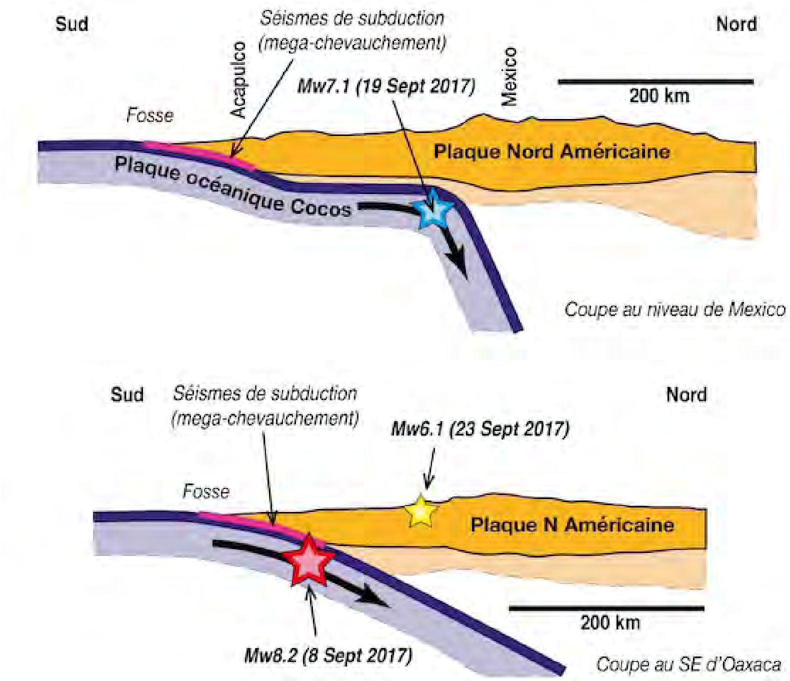


Figure 2–3 - Schematic cross-sections describing the underlying geometry of the subduction zone beneath Mexico (top) and south-east of Oaxaca (bottom), including the position of both major September 2017 earthquakes. (Source IPGP - http://www.ipgp.fr/fr/seismes-mexique-mois-de-septembre-2017 - last visited 25/01/2018).

2.2 Seismicity observation networks

Across the country, several institutions operate seismological networks with the capacity to record seismic waves generated by earthquakes. These institutions include:

- El Servicio Sismologico Nacional (SSN) de Mexico (http://www.ssn.unam.mx/), which runs a network of 61 broad band stations (i.e. seismological recording stations with a wide frequency range – from 0.1 to 30 Hz in this case).

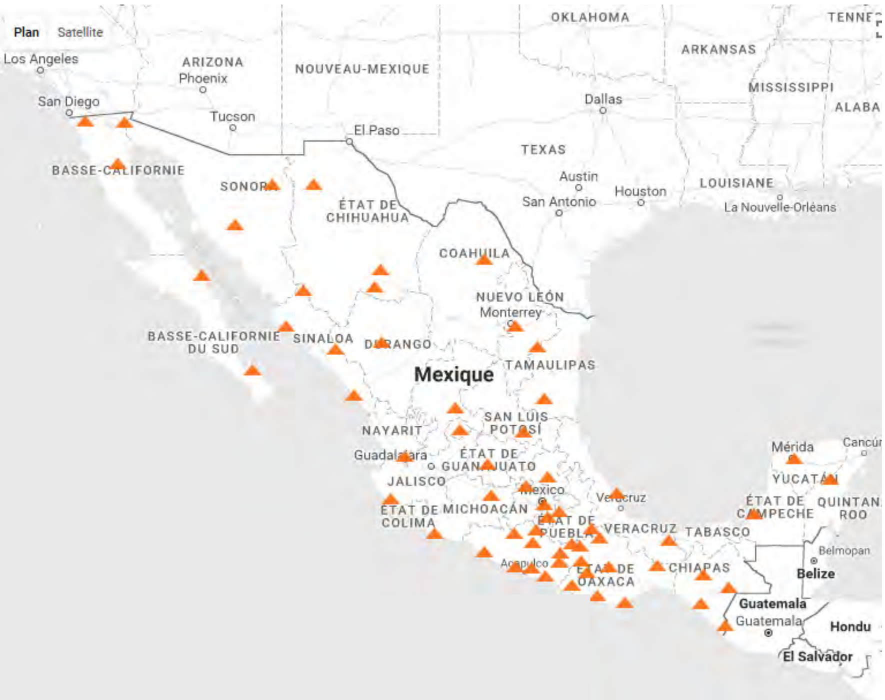


Figure 2–4 - Map of the SSN broad-band station network (orange triangles)
http://www.ssn.unam.mx/acerca-de/estaciones/

- The Coordinacion de Ingenieria Sismologica del Instituto de Ingenieria (UNAM), which is in charge of the Seismic Network for the Valley of Mexico (RSVM – 31 stations) and of a network of accelerometers in the City of Mexico itself.

Figure 2–5 - Seismological data processing center at the Instituto de Ingnieria

- The Centro Nacional de Prevencion de Desastres (CENAPRED), which monitors the volcanic activity, and most notably the Popocatepetl, and also operates a network of accelerometers (5 stations between Acapulco and Mexico, and 11 stations in Mexico City).

Figure 2–6 - CENAPRED network of accelerometric stations (left - https://www.iris.edu/hq/files/workshops/2015/05/gro_chile/docs/networks/Mexico/Estaciones_Cenapred.pdf - le 23/01/2018). CENAPRED data acquisition and processing center (right – picture taken during the visit to the observatory by the mission on November 8th 2017).

- El Centro de Instrumentacion y Registro Sismico (CIRES), which operates a substantial network of accelerometric stations in the Valley of Mexico (Red Acelerografica de la Ciudad de Mexico – RACM) and, importantly, which is also in charge of the SASMEX (Sistema de Alerta Sismica Mexicano), the earthquake warning system. When the September 19th 2017 earthquake struck, the warning system responded adequately but proved inefficient because the epicenter of the earthquake was located close to Mexico City and the triggering of the alarm coincided with the arrival of the seismic waves.

Figure 2–7 - Earthquake warning system for Mexico. The triangles correspond to the stations of the warning network and the radiating circles to the wave propagation times from the epicenter (red triangle).

2.3 Comparison with the 1985 earthquake

The most devastating earthquake ever to occur in Mexico took place on September 19th 1985, 32 years to the day before the earthquake of September 19th 2017. It caused the death of more than 10,000 people (it should be noted that this number remains an approximation as counting was stopped in the face of the rising number of casualties). In this section, both earthquakes will be compared in order to understand the difference in their respective impacts on Mexico City.

Table 2-1 lists the seismological parameters characterizing both of the above-mentioned earthquakes. They differ in nature in terms of the mechanisms at the focus with a reverse fault mechanism occurring in the contact zone between the Cocos and the North-American plates in the case of the 1985 earthquake as opposed to a normal fault mechanism within the Cocos plate in the case of the 2017 earthquake.

	September 19th 1985[3]	September 19th 2017[4]
Origin Time (local)	07h17	13h14
Latitude	18.19°N	18.40°N
Longitude	102.53°W	98.72°W
Distance from Mexico City	≈ 400 km	≈ 120 km
Depth	28 km (±3.8)	57 km
Magnitude	Mw= 8.0	Mw= 7.1
Strike (Nodal Plane 1/ Nodal Plane 2)	301/105	112/296
Dip (Nodal Plane 1/ Nodal Plane 2)	18/73	-93/-87
Rake (Nodal Plane 1/ Nodal Plane 2)	105/85	46/44

Mécanisme au foyer

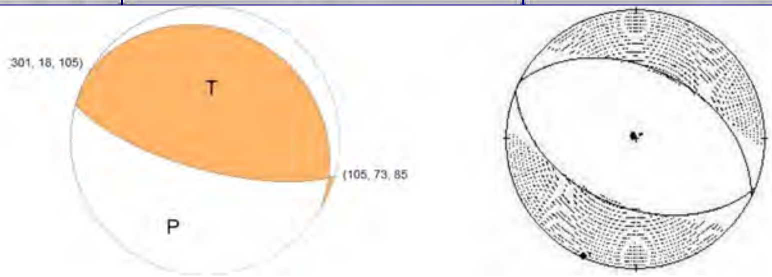


Tableau 2 1 : Characteristics of the 19/09/1985 and 19/09/2017 earthquakes.

Some of the seismological stations have been operating long enough to have been in a position to record both the 19/09/1985 earthquake and that of 19/09/2017. This is the case for the CU and SCT stations in particular. Their respective locations are indicated on Figure 2-8 (left). The CU station is deployed on an outcrop of volcanic rock at the heart of the UNAM, whereas the SCT station has been installed on the sedimentary infill which constitutes most of the city's subsoil. In terms of spectra, this means that far greater maximum acceleration values are recorded at the SCT station, on account of the lithological site effect beneath it.

When comparing the spectra on hard rock for the 19/09/1985 and the 19/09/2017 earthquakes, one can directly observe the spectral signatures of these earthquakes (Figure 2-8, top right). A clear difference can be noted between both events as the 2017 earthquake appears to be far more energetic for periods of less than one second. Spectra recorded by the SCT stations (Figure 2-8, bottom right) include the soil response and they display greater accelerations in the case of the 1985 event, in agreement with the fact that the SCT station is located in the area most affected by the 1985 earthquake.

Using all of the accelerometric recordings available for Mexico City, spectral accelerations at 1 s and 2 s were determined for the 19/09/1985 and the 19/09/2017 earthquakes. The results are presented in Figure 2-9 in the form maps which also feature the position of collapsed or severely affected buildings (dots graded in color from white to blue). Several points of information can be inferred from these maps:

- The maximal spectral acceleration for the 19/09/1985 earthquake occurs at periods of 2 seconds, whereas it occurs at periods of approximately 1 second in the case of the 19/09/2017 event;
- Because of the difference in the spectral signatures between both earthquakes and the lateral variation in the sedimentary thicknesses across the city, the areas subjected to the strongest accelerations are not the same. The area which sustained the strongest accelerations in 2017 is located by the shores of the former lake, close to the so-called transition zone where sedimentary thicknesses are between 15 and 35 meters. In the case of the 1985 earthquake, the strongest accelerations occurred in an area located directly to the east, towards the interior of the basin, where the sediment layers are thicker than 30 m;
- Incidences of destruction are located around areas of maximum accelerations;
- The typology of buildings impacted differs between the 1985 and the 2017 events. In fact, instances of structural damage that occurred in the wake of the 1985 earthquake were observed in relatively high buildings, whereas they were observed on buildings of average height in 2017. This observation can be explained directly by the recorded maximum acceleration periods. The fact that maximum acceleration took place at longer periods in the case of the 1985 earthquake (2 s) than in the case of the 2017 earthquake (1 s), means that higher buildings were impacted in 1985 compared to 2017.

[3] *USGS (https://earthquake.usgs.gov/earthquakes/eventpage/usp0002jwe#executive – last visited on 24/01/2017)*
[4] *Servicio Sismologico Nacional (SSN), 2017. Reporte Especial, SIsmo del dia 19 de Septiembre de 2017, Puebla-Morelos (M 7.1)*

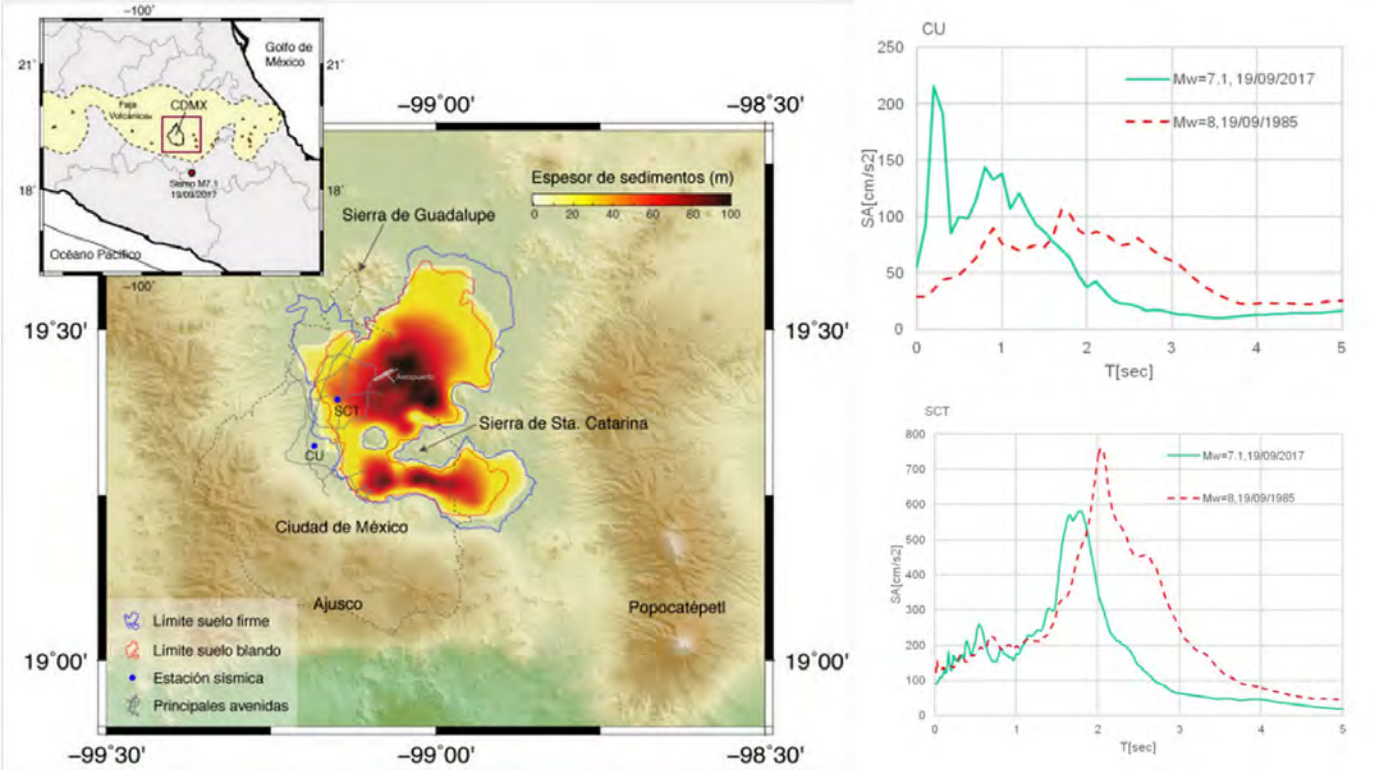


Figure 2–8 - Location of the CU (on rock) and SCT (on sediments) stations against a background of sediment isopach map (left map) [5]. The respective recorded spectra of both stations for the 19/09/1985 and 19/09/2017 earthquakes are displayed on the right (Pr. M. Ordaz Schroeder, personal communication). The solid blue line pertains to the 2017 earthquake and the dotted red line to the 1985 event.

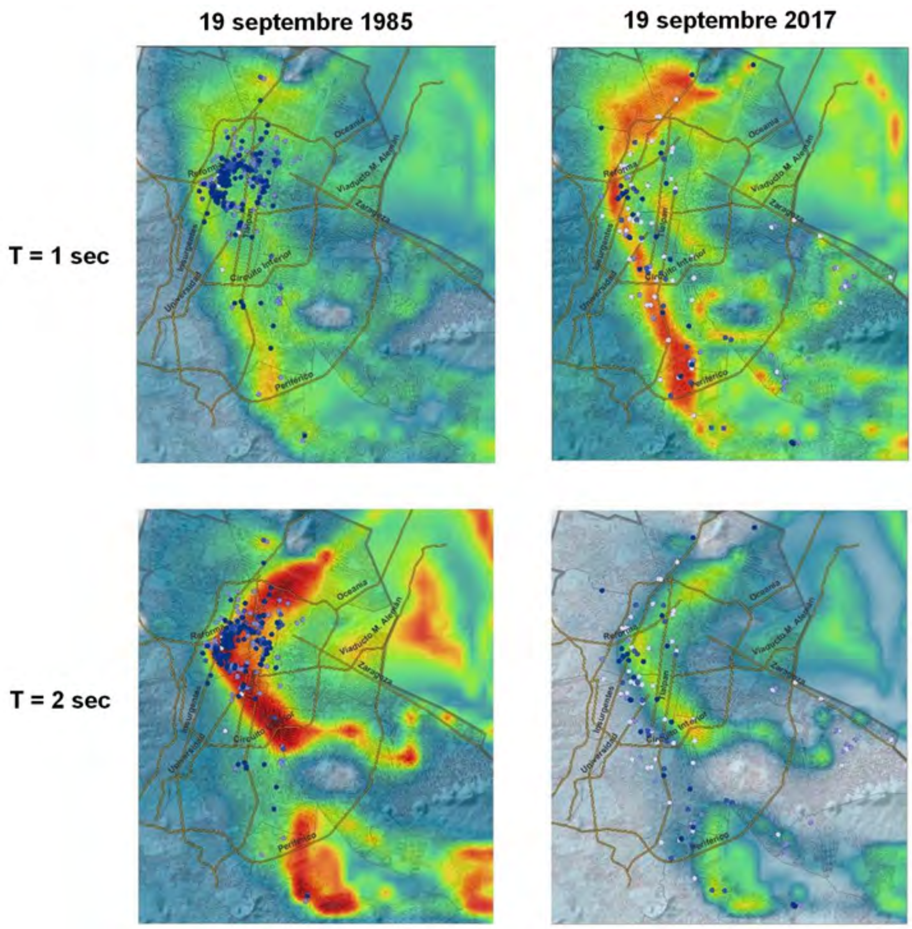


Figure 2–9 - Spectral acceleration maps calculated at 1 s (top) and at 2 s (bottom) for the 19/09/1985 (left) and 19/09/2017 (right) earthquakes (Pr. M. Ordaz Schroeder, personal communication). Red corresponds to the strongest acceleration values and blue to the weakest. Dots, graded in color from blue to white, indicate damaged/collapsed buildings.

2.4 Definition of the seismic hazard in Mexico

In view of the collected information, which is not exhaustive, it seems that there is no regulatory seismic zoning map of the whole country, which would be the equivalent of the seismic zoning map of France (probabilistic approach for a 475 year return period).

Municipal authorities are in charge of defining building codes and in several cases no such codes exist. As an alternative, many local authorities rely on “el manual de diseño de Obras Civiles (Diseño por Sismo)” of the Federal Electricity Commission when dimensioning civil engineering works [6]. In this manual, a seismic zoning of Mexico is proposed and is generally used (Figure 2-10, based on the seismic history of the region and the predicted accelerations using a probabilistic approach).

Figure 2–10 - Seismic zoning of Mexico (Manual de diseño de Obras Civiles [Diseño por Sismo] de la Comision Federal de Electricidad - https://www.sgm.gob.mx/Web/MuseoVirtual/Riesgos-geologicos/Sismologia-de-Mexico.html - last visited on 25/01/2018).

In addition, several works have been published in recent years in an attempt to provide robust input data to be used in the elaboration of a probabilistic seismic hazard zoning of Mexico. Among these, particular attention is drawn to the works of [2] which in particular proposes a seismotectonic zoning of the whole country, and of [7] which developed attenuation models specific to Mexican interplate earthquakes.

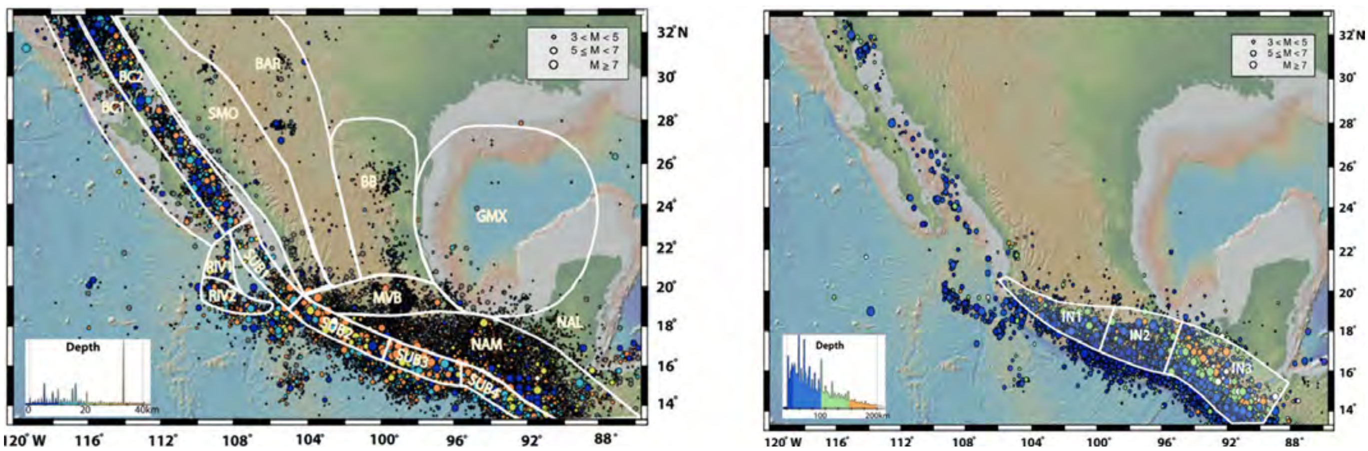


Figure 2–11 - Seismotectonic zoning of Mexico as proposed by [2]. Left: Zoning in relation to superficial seismicity (h 40 km). Right: Zoning in relation to intermediate-depth seismicity (h > 40 km).

2.5 Subduction zones in France

The Antilles (or French West-Indies) is the only French region located in a subduction zone, namely the Lesser Antilles subduction zone. In this area, the North-American plate subducts under the Caribbean plate at a rate of approximately 2 cm/year and seismic activity is more intense there than anywhere else on French territory. Seismicity catalogs show that all major types of earthquake common to subduction zones may occur in the Lesser Antilles: interplate earthquakes (e.g. the 1843 earthquake – Magnitude estimated between 7.5 and 8.0), intraplate earthquakes (e.g. 2007 event – M=7.3 and 2014 – M=6.3) and continental earthquakes (e.g. the 2004 Les Saintes earthquake – M=6.3).

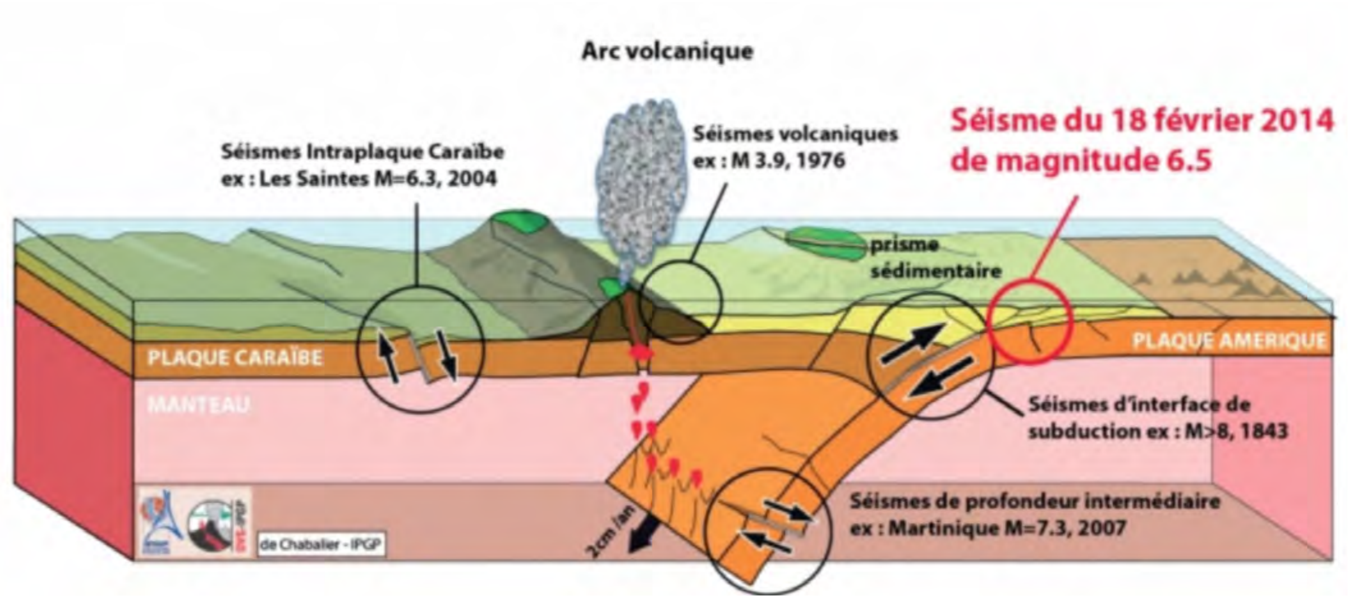


Figure 2–12 - Schematic diagram of the Lesser Antilles subduction zone. The most powerful earthquakes recorded in the area are indicated (http://www.ipgp.fr/fr/seisme-a-lest-de-martinique - Last visited on 25/01/2018).

In this context, the role of the Volcanological and Seismological Observatories in Martinique and Guadeloupe (OSVM and OSVG, respectively) is of primary importance in our effort to better monitor and understand the seismicity of this region. In addition, in view of the high seismic hazard prevailing in the region, the "Antilles Earthquake plan" (Plan séisme Antilles) was drafted in 2007 with the objective of promoting anti-seismic construction and strengthening of existing structures (http://www.planseisme.fr/-Espace-Plan-Seisme-Antilles-.html – last visited on 25/01/2018). This plan, designed for a duration of 30 years, has entered its second phase with the «Plan séisme Antilles – Horizon 2020».

2.6 Main lessons

Mexico is located within a subduction zone. This region is one of the most active seismic areas on the planet, where powerful earthquakes regularly strike. The September 19th 2017 event was a magnitude 7.1 intraplate earthquake located at a depth of 57 km, approximately 120 km from Mexico City. In comparison, the September 19th 1985 event was a magnitude 8.0 interplate earthquake that occurred at a depth of 28 km, with an epicenter located approximately 400 km from Mexico City.

The spectra associated with these two earthquakes are different. The September 19th 2017 earthquake is more energetic below one second. Spectral acceleration maps drawn for each event show that acceleration is maximum i) at 1 s and located in the lake transition zone in the case of the 2017 earthquake and ii) at 2 s and located more towards the interior of the basin in the case of the 1985 earthquake. For both events, the main instances of destruction occurred in the areas of maximum spectral acceleration. The difference in the values of the calculated spectral acceleration explains why different types of buildings were impacted in each case.

Refe rences :

[1] Servicio Sismologico Nacional (SSN), 2017. Reporte especial, Sismo de Tehuantepec (2017-09-07 23 :49 M 8.2).

[2] Zuniga F. –R., Suarez, G., Figueroa-Soto, A. and Mendoza, A., 2017. A first-order seismotectonic regionalization of Mexico for seismic hazard and risk estimation. Journal of Seismology, vol. 21, pp. 1295-1322.

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Internet links :

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https://www.iris.edu/hq/files/workshops/2015/05/gro_chile/docs/networks/Mexico/Estaciones_Cenapred.pdf

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3 Regulations

3.1 Retrospective and present-day challenges

Due to the autonomy granted by the Mexican constitution to municipalities regarding the management of their local territory, there are no common, country-wide regulations governing construction. Nevertheless, there is a will to harmonize existing texts and it should be noted that the city of Mexico regulations often act as a reference for other municipalities. In what follows, a retrospective of the main regulatory texts is presented.

1920 The first construction regulations for Mexico City were published in 1920. These very succinct rules specified certain permissible stresses depending on the types of materials used as well as the minimum dimensions for certain structural elements.

1942 The 1920 rules were first revised in 1942. Two essential concepts were introduced in order to limit the impact of earthquakes. First of all, the height of buildings was limited to 35 m and, secondly, construction works were categorized according to their function. These elements allow the shearing stress at the base of structures to be determined. This is calculated as a certain proportion (noted Cv) of the structure's own weight, taking into account the operational loads.

Figure 3–1 - Catalog of the 'Arquitectura en México 1900-2010' exhibition.

1957 The first emergency rules were introduced following the magnitude (Mw) 7.5 earthquake that took place on July 28th 1957. On this occasion, the Mexican authorities noticed that damage intensity was a function of the nature of the soil supporting the works. Consequently, a relation was introduced between soil classification, categories of engineering works and attempts at seismic dimensioning. Building categories were also revised and their number reduced from seven to three. Finally, the concept of permissible stress was complemented by limitations concerning inter-story drift as well as top lateral displacement.

1966 The 1966 rules replaced the emergency 1957 rules. The categories of engineering works, soil, and structural systems are slightly modified compared to their 1957 definitions. The main change concerns a more refined evaluation of the Cv coefficient. In addition, specific requirements regarding non-structural elements are introduced. Constructions in excess of 45 m in height or 10,000 m2 in cumulated surface area must be fitted with dedicated instrumentation, either accelerometers or strain gauges.

1976 The rules issued in 1976 stand out as the fundamental rules for modern construction. They are reorganized into a main corpus completed by specific technical appendices. In addition, we see the introduction of the concept of performance requirements as a function of the building materials used. A modern view on dimensioning that includes limit states appears as early as 1976. The main novel elements are: (i) the acceptance of some degree of ductility for a structure when subjected to an earthquake, (ii) an increase of induced torsion by doubling accidental eccentricities, and finally (iii) the parameterization of the seismic shearing stress using the structure's natural periods (concept of dimensioning spectra).

1985 The year 1985 was marked by the September 19th event. Following the collapse of a large number of structures new emergency rules were issued. The main progress apparent in the 1985 rules is the inclusion of rehabilitation and strengthening projects.

1987 The necessity to replace the 1976 rules by integrating the 1985 emergency rules led to the 1987 revision. The spirit of the 1985 emergency rules is preserved with new increased requirements regarding the value of certain parameters and construction stipulations. In particular, it is worth mentioning the increase in the zero period ground acceleration value, the inclusion of a minimum space between adjacent buildings, recommendations regarding the interaction between the ground and the structure or the presence of systems allowing the dissociation between structural and non-structural components. Finally, the responsibility of the various actors in the construction industry is clarified.

2004 The 2004 construction regulations replaced those of 1987 and are still in force in Mexico City today. It is worth mentioning the evolution in the categorization of structures, not only as a function of their use, but also as a function of their structural system. The loads are classified depending on their permanent, variable or accidental nature and the dimensioning is performed by combining them. The design and dimensioning spectra are rendered specific to the site on which the structure is erected. In addition, a retroactive principle is introduced. In the case of a damaged structure, it can be retro-fitted so that the safety requirements prevailing when the observations are made are adhered to. Finally, there is a noticeable improvement in the requirements regarding foundation systems.

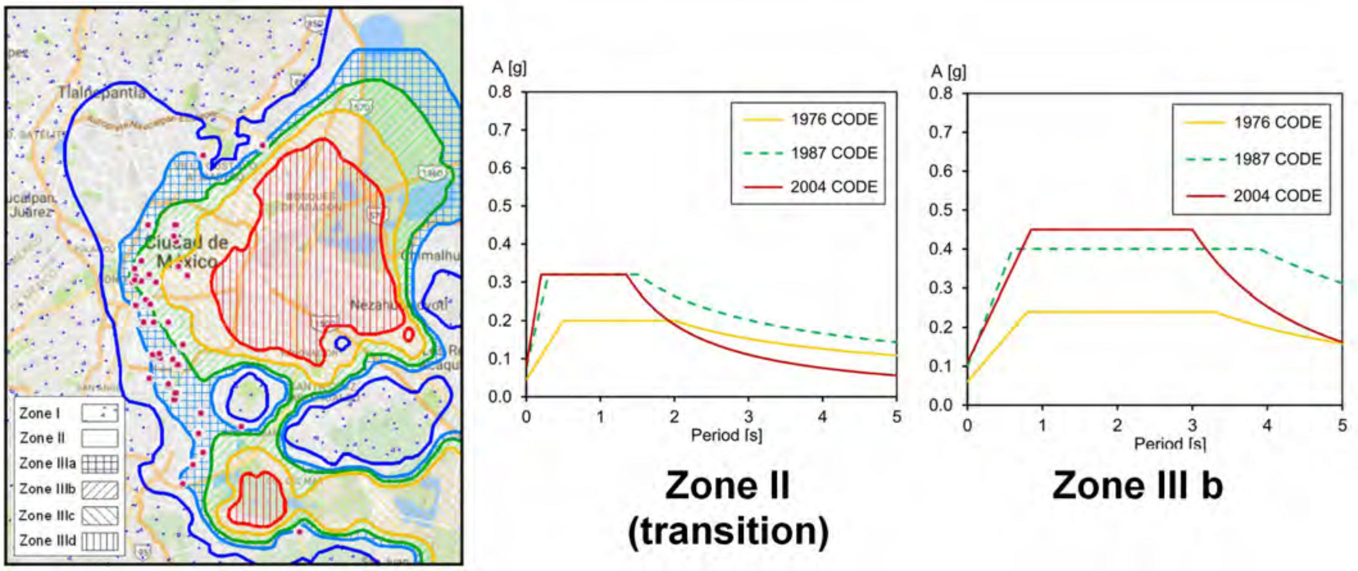


Figure 3–2 - Evolution of spectra from 1976 to 2004 for two types of soil (preliminary report 2017 - Stanford University)

On the basis of several accounts collected during our mission, we are in a position to make the following statements:

- if the construction rules established in 2004 had been respected, there would not have been such extensive damage;
- verifying that the regulations have been implemented requires significant human and technical resources;
- there are difficulties in the application of the regulations due to the interpretation of the rules by professionals in the sector.

In order to overcome these difficulties, the Mexico City authorities have initiated a substantial work with the aim of producing simplified and more broadly disseminated construction rules. Indeed, nearly 40% of residential buildings have not been studied by engineering consultant firms, mainly on financial grounds. Simultaneously, the authorities are promoting the writing of a model code that could be applied on a federal scale.

3.2 Prevailing regulations in 2017

3.2.1 Legal framework

Figure 3–3 - Cover of the CFE Manual

Since Mexico is a federal state there are no national anti-seismic regulations: each state is responsible for developing its own regulations.

However, a manual exists, namely the «Manual de diseño de obras civiles - diseño por sismo» published by the Comisión Federal de Electricidad (CFE), which is used as a reference throughout the country. The most recent edition dates to 2008 [5].

In the city of Mexico, one can avail of the «Reglamento de construcciones para el Distrito Federal» and the «Normas Tecnicas Complementarias para diseno por sismo») sometimes referred to under the name NTC 2004.

3.2.2 Mexico City regulations

The normative corpus for Mexico City (which is often copied by other municipalities in the country) is divided into two distinct parts:

- A document, regarded as the main body of the text, which aims to define the performance objectives,
- Several technical appendices that aim to clarify the technical and scientific aspects of the regulations.

This manner of presenting normative texts was introduced in 1976 in order to facilitate future evolutions. Indeed, it is easier for the authors of the technical appendices to update them in line with the evolving state of knowledge in the various fields. In contrast, any modification to the main body of the document is subject to collective approbation on the part of the government of the city of Mexico. This process requires more time and must also accommodate political imperatives.

3.2.3 Seismic zoning for Mexico City

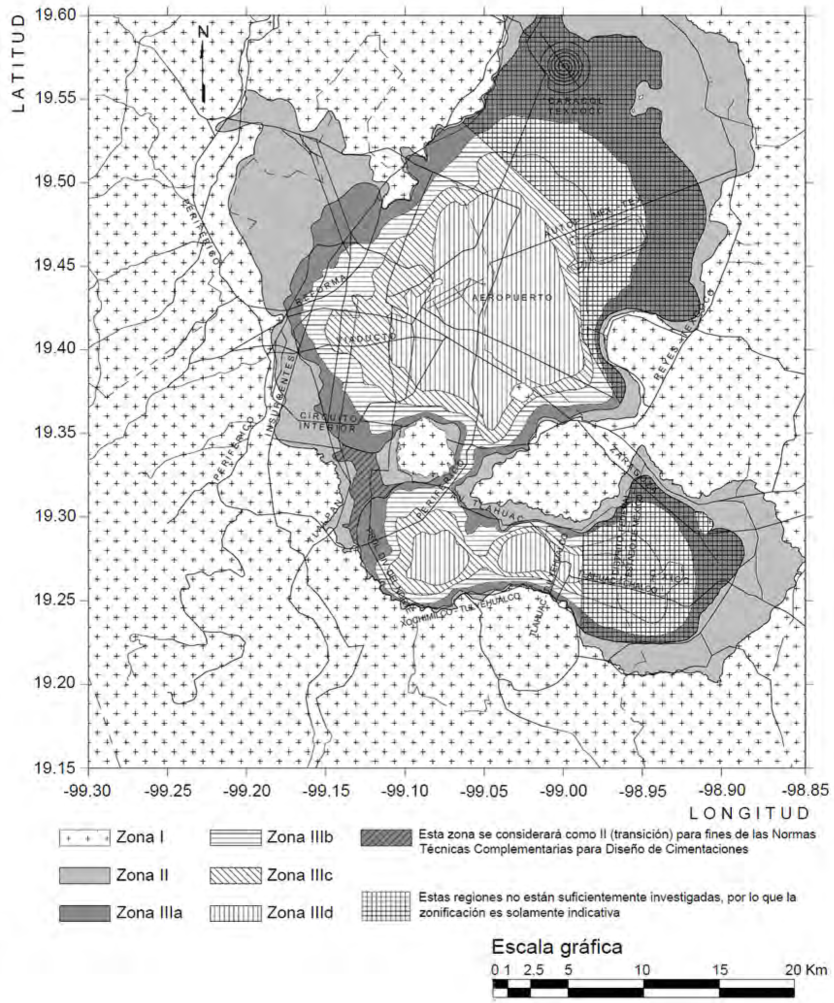
Macroscopic zoning

Mexico City regulations provide a seismic zoning map of the State of Mexico City (Federal district). This map identifies 8 zones, 6 of which are characterized as follows: zones I, II, IIIa, IIIb, IIIc and IIId. Regarding the two remaining zones, one is considered as comparable to zone II, and the other one has been insufficiently investigated. This zoning is associated with a set of dimensioning spectra.

Site-specific zoning

The seismo-geotechnical zoning of Mexico City reflects both the lithological nature of the sub-soil and the main trends in terms of the dominant soil period and maximum seismic ground motion amplification. It is similar in essence to seismic micro-zoning. A formula allowing the calculation of the natural period of a soil is also made available. This requires knowledge of the shear modulus of the soil layers involved, which must be estimated using in situ measurements. In the absence of such measurements, the period itself can be estimated using the map provided.

[5] The production of a new edition was announced on November 13th 2017 on the Federal Public Administration website gob.mx. It will be published by the INEEL (Instituto Nacional de Electricidad y Energías Limpias)



$$a = a_0 + (c - a_0)\frac{T}{T_a}\ ; \quad \text{si}\ \ T < T_a$$

$$a = c\ ; \quad \text{si}\ \ T_a \le T \le T_b$$

$$a = qc\ ; \quad \text{si}\ \ T > T_b$$

donde

$$q = (T_b/T)^r$$

Tabla 3.1 Valores de los parámetros para calcular los espectros de aceleraciones

Zona	c	a_o	T_a [1]	T_b [1]	r
I	0.16	0.04	0.2	1.35	1.0
II	0.32	0.08	0.2	1.35	1.33
III_a	0.40	0.10	0.53	1.8	2.0
III_b	0.45	0.11	0.85	3.0	2.0
III_c	0.40	0.10	1.25	4.2	2.0
III_d	0.30	0.10	0.85	4.2	2.0

[1] Periodos en segundos

Figure 3–4 - Seismic zoning map for Mexico City with spectral parameters.

3.2.4 Other aspects

The 2004 text strongly advocates that soil-structure interaction should be taken into account, particularly because of the specific nature of the soils in Mexico City. Indeed, due to the dynamic soil-structure interaction, the seismic response of a flexible structure, i.e. a structure whose foundations are embedded in deformable ground (for instance very soft soils characterized by a mean shear-wave propagation velocity Vs below 100 m/s, which is the case in the Mexico lake area) differs in several aspects from that of a similar structure founded on rigid ground (fixed base) subjected to a similar open-field stress.

For the City of Mexico this translates into dedicated normative prescriptions featuring in appendices to the complementary regulations. In particular, a simplified approach allows the system's natural period to be taken into account by considering the soil-structure interaction. The latter is estimated using stiffness parameters calculations based on the Winkler model. In addition, it is also suggested that a dedicated damping mechanism be taken into account using simplified formulae.

3.3 Expected developments

Following the 2017 earthquake, no in-depth modification of existing regulations is envisaged. Indeed, all experts agree on the fact that the extensive damage observed occurred as a result of the non-application of existing standards.

Certain details of the zoning will be updated (a modification that incidentally had already been planned prior to the 2017 events) but the fundamental principles of the prevailing regulations will not be majorly altered.

However, the preventive seismic retro-fitting of existing structures will be the object of a specific action, which will endeavor, based on feedbacks from the 2017 event, to define the intervention priorities associated with the obligation to carry out the works.

In addition, Mexican engineers hope to assess the impact of soil consolidation (linked to the history of pumping) on the dynamic response of the surface over time. In this context, they recommend that the long-term evolution of dimensioning spectra be anticipated (over 50 years or even 100 years).

3.4 Main lessons

From the information gathered, we have learnt the following:

- Seismic hazard is determined at a community- or at a federal scale (State of Mexico City),
- In Mexico City, the prevailing regulations in place since 2004 rely on seismo-geotechnical zoning with associated regulatory dimensioning spectra,
- Soil-structure interaction for the different foundation types is well established and its taking into account is strongly encouraged,
- The construction rules, which have evolved throughout the last century (in response to the 1957 and 1985 earthquakes, but not only), are now considered to be adequate and stable,
- Therefore, the in-depth revision of existing regulations is not envisaged,
- However it is planned to provide for «evolving» dimensioning spectra in order to take into account soil densification over time, a phenomenon that is highly specific to the Mexico City basin,
- The preventive retro-fitting of existing structures will be the object of a specific action.

On the last point, concerning the retro-fitting of existing structures, the mission recommends that the evolution of regulations in Mexico City continues to be monitored. Dealing with "past liabilities" is undoubtedly the main issue that earthquake engineering will have to tackle in the future.

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4 Soil and geotechnics

4.1 General geological context

The Mexico City basin is located south of the highest part of the central Mexican plateau. The city itself is built on the site of a former lake at an altitude of 2,200 m.

This elongated basin, which stretches in a NNE-SSW direction (100 x 30 km^2), is surrounded by numerous volcanoes that form part of the Trans-Mexican Volcanic Belt. On its western edge, one finds tertiary andesitic chains (Sierra de las Cruces), to the south the quaternary basalt formations (-2.6 My) of the Sierra Chicinautzin and to the north the tertiary volcanic rocks (-65 to -2.6 My) of the Sierras de Guadalupe and de Pachuca.

The Sierra Nevada dominates the eastern side of the plateau with its tertary basalt and andesite volcanoes, namely Popocatepetl and the Iztaccíhuatl volcanoes which culminate at 5,300 m. Centre-east of the plateau, are several isolated minor summits such as the Centro de la Estrella and the Sierra de Santa Catarina.

Before the Pleistocene (-2.6 to -0.012 My), the valley was open to the south and water drained though two deep valleys running through the present-day towns of Cuautla and Cuenavaca. However, the valley was sealed off during the period of volcanic activity of the Sierra Chichinautzin which started approximately 700,000 years ago during the Pleistocene, and water drainage southwards became virtually impossible as a result. A shallow lake was formed and over time lacustrine sediments, eruptive material and the products of the erosion of the surrounding relief gradually filled the ancient valley.

4.2 Lithology of the Valley of Mexico

The main formations are the following (See also Figure 4.1):

- A surface infill formation, reaching up to ten meters in thickness (1 to 10 m), which is composed of layers of loose alluvial deposits, lenses of aeolian material and a dry crust associated with the lowering of the water level in the lake;
- A series of upper lacustrine clays, reaching a thickness of 25 to 50 m, made up of alternating clay strata with varying degrees of consolidation due to surface overloads and pumping activity. Layers of more resistant material are recorded within this formation ;
- A resistant layer (la primera «capa dura») made up of sandy loam material with clay and gravel lenses of variable thicknesses. This layer is practically non-existent at the center of the basin but is up to 2m thick at the lake edges. This layer is used as an anchoring level for deep foundations (e.g. Torre Latinoamericana);
- A formation of consolidated lower clays of lacustrine origin, which reaches a thickness of 15m at the center of the basin but which is virtually absent on the edges. The formation is made up of clay layers alternating with lenses of more compact material;
- Deep deposits, 1 to 5 m in thickness, with alternating alluvial sands and gravels cemented by compact clays and calcium carbonates, and then les compact layers (known as «playas»);
- Layers of volcanic deposits and lacustrine sediments which reach a thickness of several hundred meters. The top of this formation constitutes the «segunda capa dura».

Over the past thirty years, many studies have contributed to defining the characteristics of the transition zone between the lake area and the upland zone.

4.3 Physical and mechanical characteristics of soils in Mexico City

Mexico City's underground is characterized by highly-compressible clay deposits that are drained by interlayered sandy strata. This leads to a continuous compaction of the ground surface.

Up until the 1950s, most of the city's water supply was provided by the pumping of wells drilled at depths of between 50 and 500 m. This high demand on the deep aquifers led to a significant dropping in the piezometric level. A strong hydraulic gradient occurred across the compressible clay layers as huge amounts of water were extracted at depth while the superficial water table remained unchanged. This phenomenon, by increasing the effective stress, caused an acceleration of the consolidation processes and, in turn, accentuated the degree of compaction. For instance, annual soil compaction was of the order of 35 cm/year during the 1950s when water extraction was at its maximum. Today, certain areas in the city still experience compaction at a rate of approximately 1 to 10 cm per year.

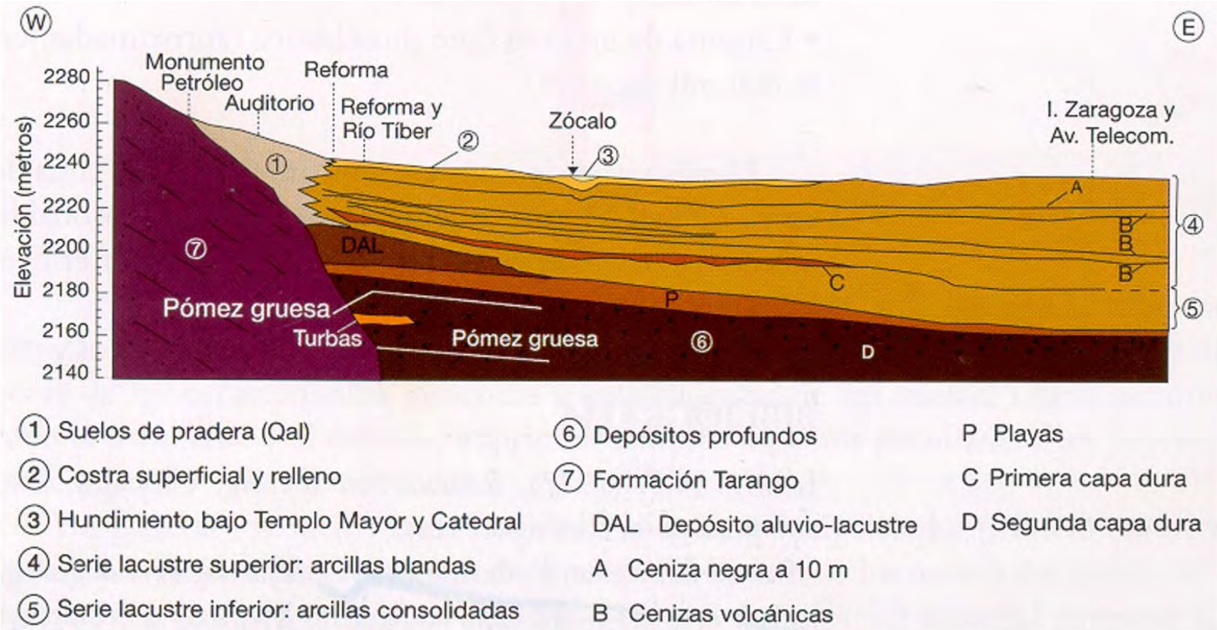


Figure 4-1 – East-west stratigraphic profile of Mexico City [1].

In the upper clay layers, the water content can reach values of up to 150 - 250 % (historic city center) and can even exceed 400 % in the lake area (Texcoco) with cone point resistance qc values, measured using static CPT (Cone Penetration Testing), often lying below 10 MPa (see appendices). In the former lake area, the volumic weight of clays over a thickness of 20 m is on average close to 12 kN/m3.

The shear wave velocity Vs can be inferior to 100 m/s or even 30 to 50 m/s over the first 30 meters depth (see appendices). The Vs,30 values (harmonic mean of shear wave velocities over the first 30 meters) can be inferior to 70m/s. The Poisson's ratio, measured using the elasticity relationships between the P- and S-wave velocities, is between 0.490 and 0.499 (personal data). In this range of soil deformation (distortion γ< 10-5) the shear modulus G (noted G0 or Gmax) lies below 5 or even 3 MPa. In the transition zone (Zone II), the average Vs values can be higher, in particular when coarser sedimentary deposits are present.

4.4 Seismo-geotechnic zoning

The city of Mexico spreads over a great variety of soils, ranging from lava and very compact soils (as in the hills) to the excessively compressible soils of the former lake.

The Valley of Mexico has been divided into three distinct zones (Figure 4-2), which correspond to:

- The upland area formed of volcanic rocks or lava flows which cover underlying sediments (Zone I) ;
- The lacustrine area with mostly clayey infills (Zone III) ;
- The transition area corresponding to the gradual change between the lacustrine- and the upland area (Zone II).

Largely based on this subdivision into large units, the "geotechnic" zoning of Mexico City also reflects the broader trends in terms of dominant soil period and maximum seismic motion amplification. Regulatory elastic spectra are assigned to these "seismo-geotechnical" zones.

It should be remembered that the areas of significant damage observed following the 1957, 1979 and September 1985 earthquakes are located in the lake area, at the edge of the transition zone. In the transition zone itself, and in the hills, destruction was minor or non-existent as in the case of the September 1985 earthquake. Relative to the emergency regulations introduced in the wake of the 1985 event (Figure 4.2-a), the 2004 zoning redraws the outline of the three zones and introduces the subdivision of Zone III (Figure 4.2-b).

In the 2004 regulatory text, acceleration spectra are provided for Zones I, II, IIIa, IIIb, IIIc, IIId.

Numerous soundings and profiles carried out over the past 15 years have led to improvements to the zoning established in 2004.

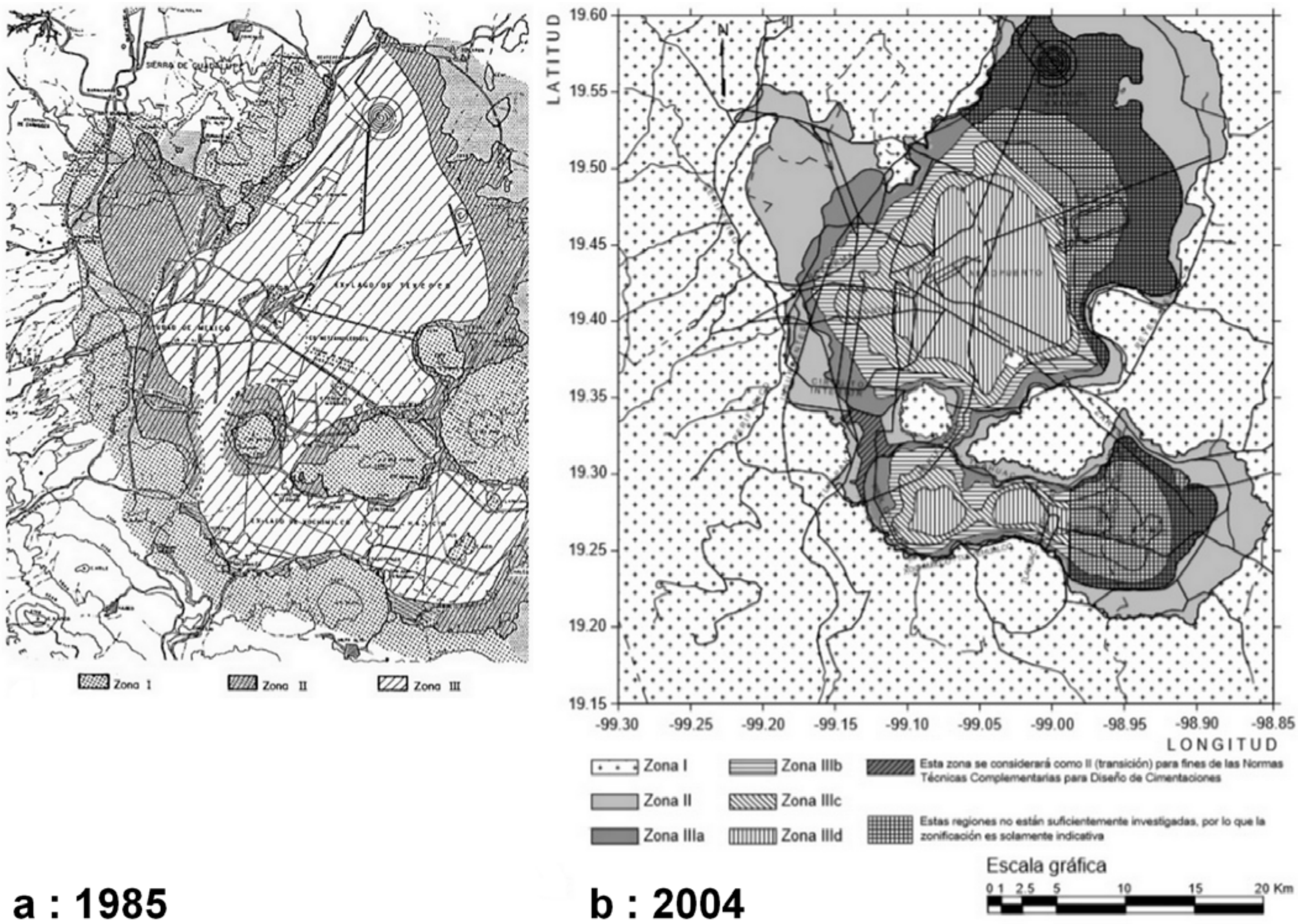
4.5 Fundamental period of the soil in Mexico City

Under 1D conditions for the propagation of the vertical S-waves, the incident- and surface-reflected fields being in phase, the T0sol period, corresponding to the first fundamental mode, is determined using the following formula (1):

T0sol = 4H/VS

(1)The single-sensor H/V method was used during this mission (see Appendices). Using the seismic background noise, it provides an estimate of the resonance frequency for the first fundamental mode (f0= 1/T0) for an accumulation of sedimentary layers overlaying a seismic substratum.

Works published since 2013provide updated mapping of clay isopach (Figure 4-3-a) and isoperiod (figure 4-3-b) curves for the Valley of Mexico.



Evolution of the geotechnical map for the city of Mexico.

Left (a) the 1985 version and right (b) the 2004 version which still prevails in 2017.

4.6 Period map and destruction map

The locations of severely damaged and collapsed buildings have been plotted on an urban background map (Figure 4.4-a) and are presented together with the H/V measurement value ranges obtained in the context of the present mission (Figure 4.4-b). The inventory of severely damaged buildings reveals a stronger concentration for zones II, IIIa and IIIb (See Appendices). A detailed study presented in the appended documents shows a rapid change in the soil period in the districts located between Condesa and Roma.

In addition, researchers suggest that soil consolidation should be taken into account when assessing the evolution of the dynamic response of the soil column. In particular, a decreasing void ratio following the “densification” of the substrate would tend to lower the fundamental period of the soil.

4.7 Main lessons

Soils in the Valley of Mexico display quite remarkable physical and mechanical properties over a thickness in excess of 50 m, directly linked to their deposition mode. Highly compressible and subject to a spectacular consolidation phenomenon arising both from natural processes and from pumping/draining of the water resources, the vertical deformation of these soils, with or without surface loading, is relentless in the area once covered by the ancient lake and in its peripheral zone.

The strong mechanical contrast between the deep soil and this compressible soil cover (0 to 80 m for the eastern part of the area) is also responsible for the dynamic effects experienced by the inhabitants and buildings on the surface.

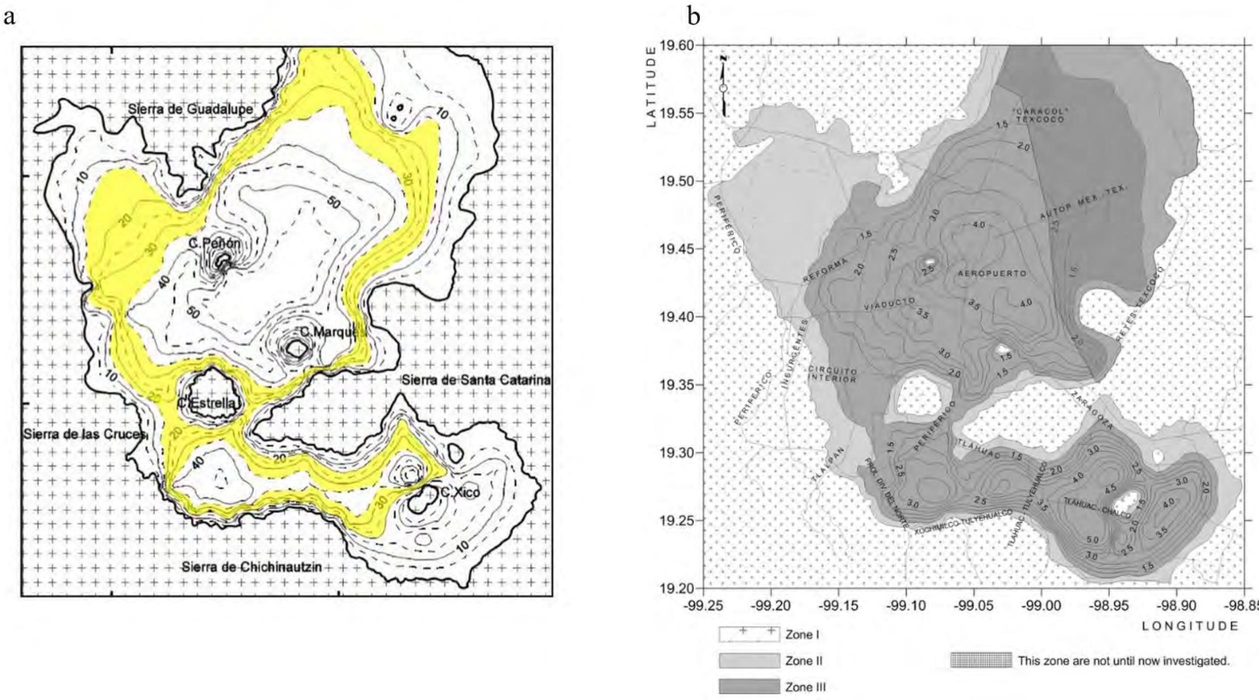


Figure 4.2 – Isopachs of infill soils (a) and isovalue curves for the fundamental period T0 sol (b) for Mexico City [2].

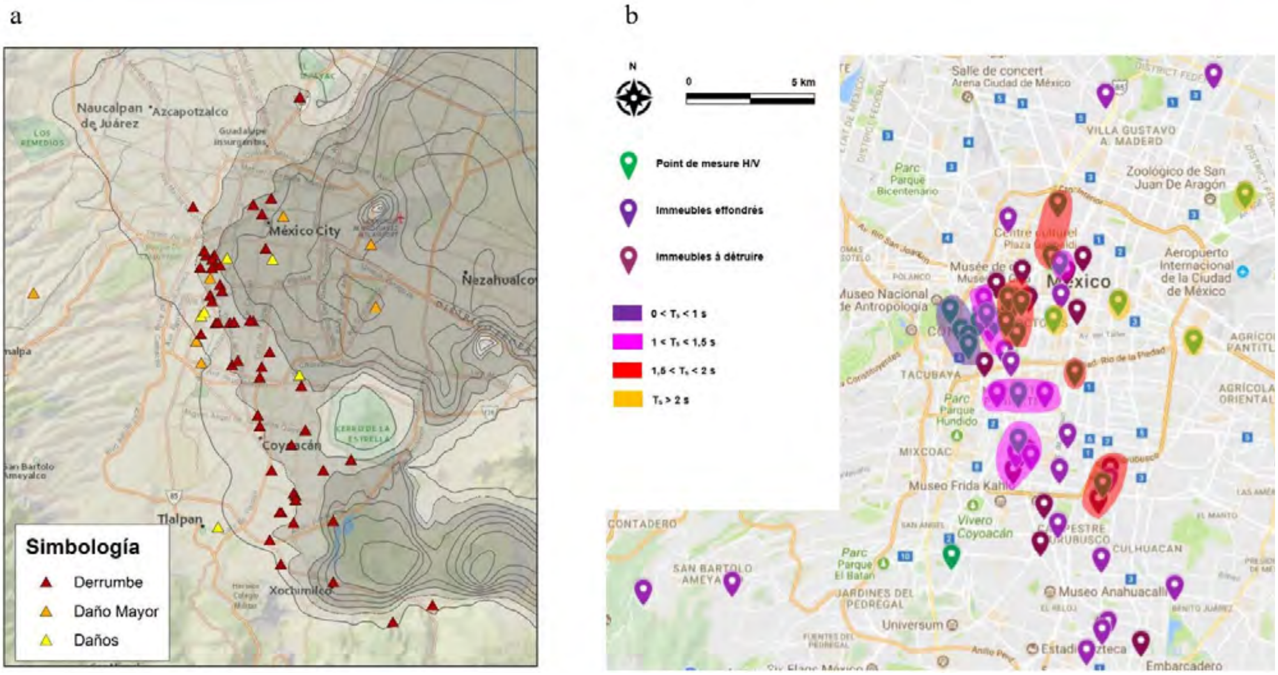


Figure 4.3a – Destruction map for the 19/09/1985 earthquake featuring collapsed structures (derrumbes), severely damaged structures (daños mayores) and significantly damaged structures (daños) [1].

Figure 4.4b –Map of H/V measurements and ranges of T0 sol periods measured by the AFPS mission.

The site effect is very pronounced in Mexico City with the amplification of seismic motion in overlying soils. This effect is differentially solicited depending on the spectral signature of earthquakes, as evidenced by the significantly different damage distributions observed for the 19/09/1985 and the 19/09/2017 earthquakes (see Appendices). In 1985, a deeper zone of the former lake was most affected (Zones IIIb and IIIc).

In 2017, however, the geotechnical zones involved are Zones II, IIIa and IIIb. In 1985, instances of destruction are distributed within the north-western quadrant, whereas in 2017 this distribution stretches more towards the southern and the western shores of the former lake. In 2017, we are dealing mostly with damage on the scale of one or a few peripheral structures, rather than district- scale damage.

Before 1985 (when the 1976 text was in force), the three main zones (hills, transition area, lake) had been mapped and their delimitation and subdivision were subsequently clarified after 1985 and again after 2004

The distribution of destructions within specific geographical areas in 2017 vindicates the quest by Mexican engineers for ever more refined zoning which accurately describes site effects and which takes into account the contrast in spectra as one moves from one zone to another.

We were able to measure these changes in the fundamental period using a hand-held device to measure the seismic background noise and a H/V method. Limitations in accurate zoning can be explained by the 2D and 3D effects arising from rapid changes in the nature of the lithology and/or thickness of the soil.

Soil amplification effects for thicknesses of between 15 and 35 m appear evident in view of the distribution of collapsed buildings. On the basis of observations made in the field, it appears that surface seismic motion selectively causes damage to certain structures which are distributed over a large area.

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[2] J. Martínez-González, J. Lermo, F. Vergara-Huerta, E. Ramos-Pérez, Avances en la zonificación sísmica de la Cuidad de México y zona de chalco, edo. de mex., propuesta de nuevo mapa de periodos dominantes para las NTC para diseño por sismo del reglamento del D.F. XX Congresso Nacional de Ingenería Sísmica, Acapulco, Mexico (2015).

5 Foundations

5.1 Main issues involved

The city of Mexico is well known for the extraordinary scale of its soil compaction phenomena under static conditions: this compaction can arise from the slightest surface loading or, more simply, from the long-term pumping of deep water resources which accelerates soil consolidation.

Regardless of the chosen foundation type (shallow- or deep foundations) all projects have to be conceived with this phenomenon as an input data. Furthermore, apart from the upland zone and certain sectors in the transition zone, the geotechnical substratum is often too deep, in technico-economic terms, to be reached and to be used to anchor deep foundations which have the advantage of end-bearing capabilities. In some cases, a sandy formation, a few meters thick, is sought out as anchoring, as for instance for the piles of the Torre Latinoamericana (Colonia Centro, Delegación Cuauhtémoc) which was built in 1956 and subjected to earthquakes first in the same year and subsequently in 1985 and 2017. This tower is 196 m high with a square base measuring 34.4 x 34.4 m.

In addition, items of infrastructure must be able, under seismic load, to accommodate lithological site effects which translate notably into significant horizontal motion amplifications. One particular cause of these amplifications is the presence of 10 to 60 m thick alluvial deposits, including highly compressible, water-saturated clays.

In this context, the effects of soil-structure interaction are pronounced and can be separated into kinematic effects on the one hand, and in particular horizontal motions characterized by a high surface amplitude (dg in the EN 1998 standard or EC8), and, on the other hand, the effects of inertial forces generated by the structure's mass and transmitted to the ground through the foundation components.

5.2 Foundation typology

The foundation types most characteristic of Mexico City are presented in Figure 5.1 and 5.2.

Shallow footing foundations may be used (Figure 5.1a) for buildings that apply a small load onto the supporting soil (1 to 2 stories high). On the compressible soils of the lacustrine zone, even applying a 10 kPa load is already likely to cause compaction over several tens of centimeters. In the case of buildings a few stories high, the bearing capacity limit is likely to be quickly reached and floating raft foundations are frequently employed, along with a buried, uninhabited compensation level provided that there is no risk of flooding from a water table close to the surface (Figure 5.1b).

Deep foundations, such as piles, are frequently required in the lake zone. One possibility is to concentrate the piles or barettes underneath the vertical loads (Figure 5.1c) or to have denser grids under the shear walls and circulation zones (Figure 5.2a, 5.2b and 5.2c).

The anchoring soil can be quite deep in the lacustrine zone (30 to 45 m) requiring deep foundations for which floating piles may be used (Figure 5.2a). In this case, the pile bases do not rest on a more rigid, deep soil. Instead the piles rely on the lateral resistance exerted along the shaft, which is made either of concrete or steel. Increasingly used from the 1960s onward, this technique presents the advantage of reducing the differential compaction between the building and the surrounding soil.

In some cases the pile base may be extended using a steel point with a smaller diameter in an attempt to reach the top of a more compact geological horizon. This penetrating point technique (Figure 5.2b) is rarely used and is only encountered on a few dozen structures. Certain buildings use a system of interlocking or overlapping piles (Figure 5.2c).

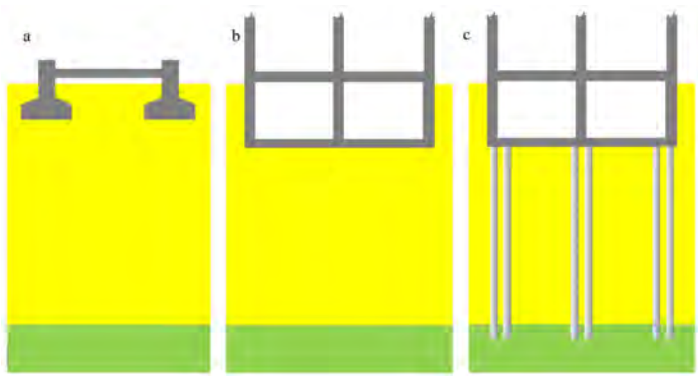

Figure 5.1 – Example of foundations used in Mexico City. Shallow foundations: pad or- or strip footing foundations (a),floating raft with lost compensation level (b) and piled raft foundations (c) with piles added underneath the structure vertical loads. Figure from [1].

Let us now look at floating piles in more detail (Figure 5.3a and 5.3b). As a surface-spread load is applied, the piles (or rigid inclusions) are solicited directly by the load applied to their tops, but also by the friction exerted by the surrounding soil as it becomes compacted by the load generated by the structure's weight. In the upper part, the soil is more compacted than the foundation, while in the lower part the foundation is more compacted than the soil. Hence, there is neutral plain for which the compaction of the soil and that of the foundation are identical.

In Mexico, these Type I piles (Figure 5.3a) correspond to what are termed "inclusions" in the French ASIRI reference base. Type II piles only utilize positive shaft friction. The pertinence of the use of Type I piles in Mexico City was demonstrated by Zeevaert in 1957 and, in the 1960s, technical literature described numerous examples showing the benefits arising from negative friction and the effects of pile grouping.

In Mexico City, buildings stand on top of compressible soils that are undergoing consolidation. One foundation technique involves using a piled raft, with piles anchored into the substratum: the tops of the piles actually pass through the raft which takes the form of a casing. These are adjustment piles (Figure 5.3b and 5.3c). The floating raft can thus slide along the piles which act as rigid inclusions. The uniform load applied to the ground by the raft is partially transferred onto the inclusions by negative friction and group effect. A device, which caps the pile tops and which is anchored into the raft, fastens the elements together and prevents compaction caused by the weight of the structure. This system is put in place essentially to compensate for any soil movement triggered by the building and, by so doing, to reduce the height of natural steps that might develop between the building and the street level.

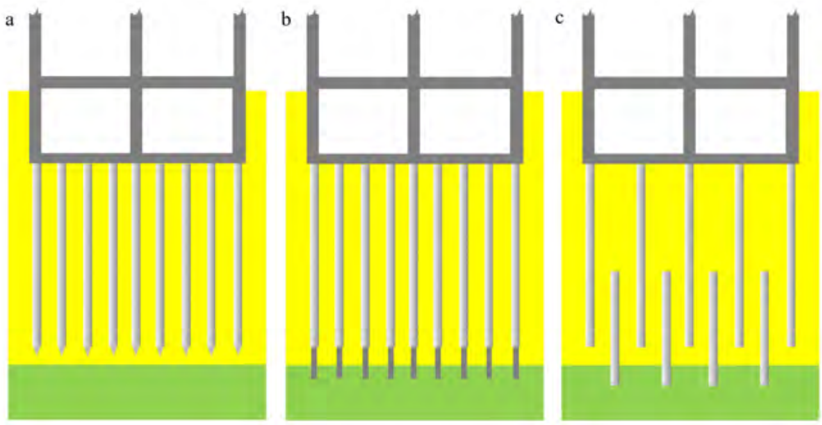

Figure 5.2 – Example of deep foundations used in Mexico City. Floating piles (a), piles with steel penetrating points (b) and overlapping piles [2] (c). Figure from [1].

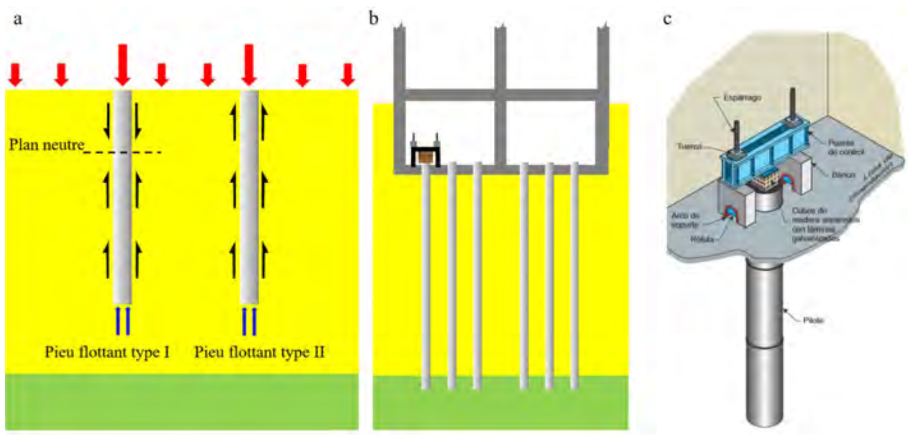

Figure 5.3 – Type I (inclusion) and type II floating piles (a). Adjustment piles (b and c). Figure from [1]. Source for (c): http://tgc.com.mx/tgc/wp-content/uploads/2013/11/Pilotes-decontrol.pdf

5.3 Damage to foundations

The buildings examined during this mission were, for the most part, 6 stories or more in height and, therefore, more than likely built on pile foundations: however, in many cases this could not be confirmed. To our knowledge, no spectacular pathologies were reported or observed for shallow-foundation type structures.

Certainly, some additional compaction effects cannot be ruled out for shallow-foundation buildings, but, according to expert architects and researchers at the UNAM, visible deformations at ground level are sometimes difficult to distinguish from the overall compaction process affecting Mexico City.

Moreover, no tilting of any pile-foundation structure was reported or observed as had been the case following the 1985 earthquake. Nonetheless, our attention was drawn to separation phenomena between the street surface and the base of several structures (Figure

5.4). In these cases, which involved buildings at least six stories in height, structural pathologies were also visible. We selected a number of examples which are described below.

Figure 5.4 – Avenida Juárez (Delegación Cuauhtémoc, Mexico)

The building featured in Figure 5.4 is located close to the historic town center, not far from the Torre Latinoamericana (ancient lake area). Construction teams are installing a mask between the two buildings, more than likely in order to minimize the visual impact of the differential horizontal spacing. In this case, it seems that the existing vertical deformation of the soil became aggravated as a result of the 19/09/2017 earthquake, causing irreversible rotations of one or both of the structures. At the base of the dark-colored building (with the construction netting), a vertical separation is visible with a downward relative displacement of the pavement (10 to 20 cm). We were unable to observe the presence of potential foundation piles or the buried compensation level through the gap that had opened between the ground floor and the street level. A seismic background noise measurement was carried out opposite these buildings yielding a soil period of 1.52s.

On the Calle Durango (in the transition zone), another separation phenomenon between the pavement and the ground floor of an eight-story building is visible. The differential vertical deformation seems to betray the presence of "hard" points that could be piles (see Appendices). Following discussion with Pr. Auvinet, it appears that the more pronounced emergence of end-bearing piles as a result of an earthquake is a well-known phenomenon.

For buildings whose structure is visibly damaged, we also note that, even when the superstructure shows signs of strong earthquake-response movements, deformations at the soil-structure interface are not always obvious and are sometimes non-identifiable.

This is the case for two selected examples: a corner building located on Calle Morelia in the Colonía Roma (Figure 5.5) and building number 872 located on the Avenida Cuauhtémoc (Figure 5.6). The latter is situated close to an area where structures were destroyed by the earthquake at the junction between the Calle Concepción Beistegui and the Calle Yacatas.

One measurement was performed near the Calle Morelia and another on the Calle Yacatas. At peak frequency, the periods were 1.79 and 1.23 s, respectively.

We were not in a position to examine any pile tops and their embedding and therefore could not come to any conclusion regarding the momentum induced by the inertial effects, or the potential ovalization of the surrounding soil due to the relative motion of the piles. In 1985, the plasticization of some of the pile tops had been recorded following in situ diagnostics.

We did not observe any pronounced interaction impact between the piles and the rafts or on the stringer networks, such as the increase of added momenta due to hard points generated by the end-bearing piles.

Figure 5.5 – Calle Morelia (Delegación Cuauhtémoc, Mexico)

Figure 5.6 – Avenida Cuauhtémoc (Delegación Cuauhtémoc, Mexico)

As pointed out by Pr. Auvinet, resonating effects having for the most part impacted on lower buildings compared to 1985 (i.e. between 6 and 11 stories high) the momenta generated by inertial effects on pile tops were less in 2017. In 1985, certain poorly designed buildings had been reduced to rubble.

Concerning the reinforcement of soil using rigid inclusions, in the strict sense, we did not obtain any information feedback regarding attested damage. Soil preloading using vertical drains is a soil improvement technique that is currently being implemented in the construction of the runways at Mexico City's future airport. On account of Mexico city's geotechnical context, this method cannot be envisaged in urban areas because of the compaction that loading induces on the immediate surroundings.

In order to limit the compaction induced by the loading imposed by roadways, developers sometimes choose to replace the existing surface soil (infill, clay) with volcanic slag aggregate, which is less dense.

In the case of subterranean structures, only a few incidences of damage to the ventilation shafts of a cut-and-cover section of the Mexico City Metro have been detected (pr. Auvinet).

Thanks to the fitting of interstitial pressure cell instruments in close proximity to the new Mexico City airport construction site, a slight transitory overpressure of a few kiloPascals was recorded during the September 7th and 19th 2017 earthquakes.

5.4 Main lessons

As a first analysis, and in the context of the structures examined, we can say that the foundations put in place in the lacustrine zone have, in the vast majority of cases, met their principal objective of contributing to the stability of the structures.

Certain pathologies can certainly be identified, and more are suspected, such as a strong solicitation of the foundations at embedding levels or cases of differential compaction, however they are not as spectacular as those recorded in 1985.

Faced with acute compaction phenomena associated with buildings on highly compressible soils, Mexico City engineers have acquired considerable experience regarding adequate foundation techniques. Solutions implemented under static conditions, such as the transfer of vertical loading by ensuring deep end-bearing foundations, have also proven to play a stabilizing role under seismic loading.

These techniques have been further improved on the basis of feedback received following the dramatic September 19th 1985 events. The seismic solicitation, the soil dynamic response and structure typology differ between 1985 and 2017, but we can confirm that none of the flagrant pathologies recorded in 1985 (e.g. the tilting of buildings due to the lack of foundations) have been observed in 2017.

References

[1] G. Auvinet, E. Méndez, M. Juárez, The Subsoil of Mexico City. Vol. III. Three volumes edition celebrating the 60th Anniversary of The Institute of Engineering. UNAM (2017).

[2] ASIRI. Recommandations pour la conception, le dimensionnement, l'exécution et le contôle de l'amélioration des sols de fondation par inclusions rigides. IREX. Presses des Ponts (2012).

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6 Damaged buildings

6.1 Main structure typologies

Analysis of the observed damage to buildings was conducted as a function of their structural typology. This concept encompasses the construction principle (masonry, concrete, etc.) on the one hand, and the general geometry of the structure (height, number of floors, etc.) on the other. These two parameters were selected on account of their significant influence on the dynamic response of a structure, regardless of its typology.

Historic monuments apart, four typologies have been determined with a good general correlation between the number of floors in a building and its mode of construction. The identified typologies are outlined below:

- Masonry buildings: These buildings are for the most part individual residences and small businesses, often constructed prior to the 1980s (Figure 6.1). The supporting elements are often of wood or brick. They are generally low buildings that do not exceed three stories in height;
- Concrete-frame buildings with in-fill masonry walls: These buildings are typically high-rise residential blocks with an ”open” ground level used as a car park (Figure 6-2). The masonry infill walls are made of brick and in some cases of concrete block, or both. Concrete cross bracing is sometimes encountered in the vertical walls of such constructions (Figure 6-3). These are often small apartment buildings, rising to a height of 3 to 10 stories;
- Reinforced concrete buildings with shear panel bracing: this category corresponds to residential or office-space high-rises, comprising between 10 and 15 floors, (figure 6-4). They are often frame-built structures with concrete floor slabs. Shear walls are present in the circulation and shaft areas and sometimes on the façades;
- Concrete-, steel- and mixed frame high-rise buildings: These buildings are mainly office or residential high-rises. The frame is built using metal profiles and the floor is constructed of mixed slabs on steel sheeting (Figure 6-6). The façades are made of non-structural components such as glass cladding. These structures commonly exceed 15 floors in height.

Figure 6 1 - Masonry building

Figure 6 2 - Concrete-frame building with masonry infill

Figure 6 3 - Concrete cross bracing

Figure 6 4 - Common reinforced concrete buildings

Figure 6 5 - High-rise concrete buildings

Figure 6 6 - High-rise buildings of steel- or mixed frame construction

6.2 Collapsed buildings

At the date when the mission started, most of the collapsed buildings had already been cleared away. Therefore, the study of these structures relies on information collected in the course of the emergency diagnostics missions. In total, more than 14,000 buildings were the subject of such inspections in Mexico City. The total number of collapsed buildings was 44. For the vast majority of these, three observations can be made:

- **Their location coincided with the "geological transition zone"**,corresponding to more homogeneous lacustrine and colluvial deposits on the edge of zones IIIa and IIIb (Figure 6-7) ;
- **Their construction type was reinforced concrete frame with masonry infill**. (Figure 6-9, 6-10, 6-11);
- **They were between 4 and 8 floors in height**. Figure 6-8 displays the distribution of collapsed buildings as a function of the number of floors for 32 buildings;
- **Their construction predates the 1990s**. It is worth noting that only one recent building (less than five years old) collapsed.

In partially collapsed buildings, it appears that destruction may have been caused by the failure of a single floor (including the ground floor) (Figure 6-12). It seems, therefore, that the relative rigidities of the floors played a significant role, be they linked to the building's original design or to localized loss of rigidity arising from its dynamic response (e.g. loss of masonry infill).

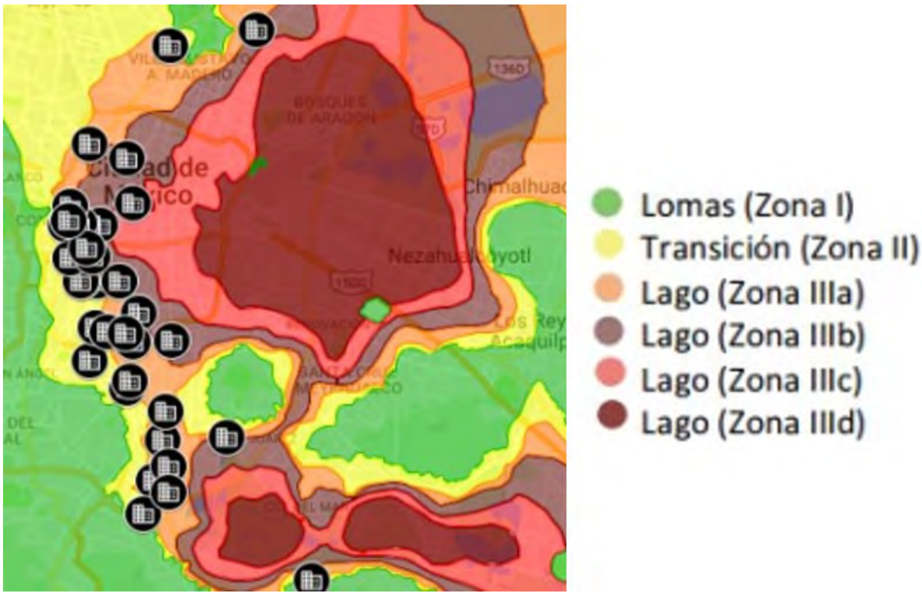


Figure 6 7 - Geographical distribution of collapsed buildings

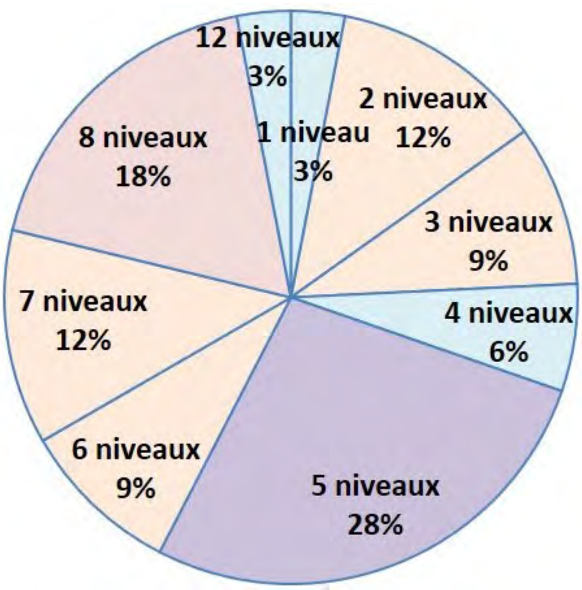


Figure 6 8 - Distribution of collapsed buildings as a function of the number of floors

Figure 6 9 - 9 floors

Figure 6 10 - 6 floors

Figure 6 11 - 8 floors

Figure 6 12 - 5 floors

Photos : www.huffingtonpost.com.mx/2017/09/23/fotos-el-antes-y-despues-de-los-edificios-derrumbados-en-cdmx_a_23220020

6.3 Damage observed in non-collapsed buildings

6.3.1 Damage linked to typology

In this section, we look in detail at the nature of the observed damage as a function of the typologies described above.

- **Low masonry buildings** : In general, this type of building suffered very little damage as a result of the September 19th 2017 earthquake. Some instances of slight collisions have been reported, mainly when the building in question was in close proximity to a building belonging to a different category.
- **Concrete frame buildings with masonry infill** : This building type was by far the type most affected by the September 19th 2017 earthquake (Figure 6 13).

Recurring damage occurred to the masonry components. Two main mechanisms were at work in the infill panels.

- The first involves the out-of-plane displacement, and subsequent fall, of all or parts of the infill bricks making up the masonry walls (Figure 6-14). This type of damage occurred following movements perpendicular to the walls and/or a torsion of the building. This mechanism was observed in walls with or without concrete stiffeners.
- The second involves the presence of 45° diagonal cracks, typical of shear failure of the infill panels (in-plane failure) (Figure 6-15). This demonstrates that the braces failed to deal with the stresses involved.

Figure 6 13 – General view of a damaged building

Figure 6 14 - Out-of-plane failure of masonry infill

Figure 6 15 - Shear failure of the infill

This is also the building type for which most of the structural damages were observed.

- For some of these constructions, significant damage was observed at the post-beam junctions (Figure 6-16), in particular on the first and second floors.
- On rare instances, beam failure was observed (Figure 6-17). These failures are counter intuitive as they present the appearance of shear strength failure (45° cracks) even though they occur at half-span, where flexural strength failure (vertical cracks) would be expected. It is likely that, in these cases, the masonry infill and its deterioration led to the transfer of some parasitic stress to the beam.

Figure 6 16 - Post-beam junction failure

Figure 6 17 - Shear failure of a beam

It is worth noting that a strong degree of selectivity applies in this category. Indeed, while most of the damaged buildings belong to this type, many buildings in this category do not display any damage at all. This phenomenon is all the more striking as it is encountered within a single district where soil conditions could be deemed uniform and where constructions visibly date from approximately the period. However, we should note, that independently of the thickness of soil infills in the Mexico Valley, the soil period map sometimes shows very marked variations at district scale.

- **Reinforced concrete buildings with shear panel bracing** :

  This type of building suffered relatively little from the recent earthquake. On rare occasions, shear cracks (45° diagonals) were observed on some reinforced concrete panels (Figure 6-18, 6-19) as well as on short posts (Figure 6-20).

- **Concrete-, steel- and mixed frame high-rise buildings** :

  Despite the significant flexural and torsion displacements (several tens of centimeters), this buildings of this type suffered very little from the earthquake. In rare instances, breakage of non-structural glass cladding is visible.

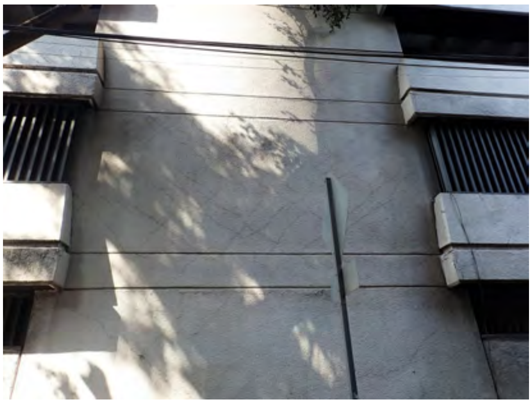


Figure 6 18 - Shear cracking of a panel

Figure 6 19 - Appearance of the shear crack (detail)

Figure 6 20 - Short post failure

6.3.2 Damage non-dependent on typology

The kinds of damage described in this section depend either on the building's surroundings, or on their non-structural components.

- **Tilted buildings** :

  Instances of slight tilting were observed in some buildings (Figure 6-21). These movements may be triggered either by the localized rupture of the foundation system, or by the soil compaction that takes place during a seismic episode. In view of the soil characteristics in Mexico City, the second hypothesis cannot be ruled out. It is worth mentioning that some of the buildings displaying this type of behavior were still in use, with apparent disregard for the potential consequences on their static balance.

- **Partial deterioration of the sol interface** :

  Deterioration and notable displacements (of the order of ten centimeters) have been regularly observed on the soil surface in close proximity to buildings. In some cases, a void was visible underneath the building, indicating a partial decoupling between the foundation system and the ground.

- **Collisions between buildings :**

  Building collision phenomena were observed. Some witnesses tell of experiencing strong shocks as a result of collisions between buildings, some of which were not reoccupied following the earthquake. However, in most cases the contact zones remain very limited (Figure 6-22) and the structural impacts quite low. This kind of damage mainly concerned 2 to 4 storey buildings. For recent constructions, the width of the building separation joints proved adequate.

- **Fall of non-structural elements :**

  The inside of damaged buildings sometimes exhibited instances of the fall of suspended ceilings and the destruction of partition walls. At the time when the mission took place, such damage was only observable in buildings that had remained unoccupied. To the outside of buildings, a number of glass elements (Figure 6-23), acroteria and planters reportedly fell.

- **The "Corner" effect** :

  The "corner" or "domino" effect refers to a phenomenon where more pronounced damage is observed in buildings located at street corners. While significant damage was indeed observed in the case of certain corner buildings, the same was true for buildings located elsewhere along the street line. As it stands, the validity of this hypothesis remains unproven and no conclusions were drawn in the course of the present mission.

Figure 6 21 - Tilting (left) of a building

Figure 6 22 - Collision between buildings of different typologies

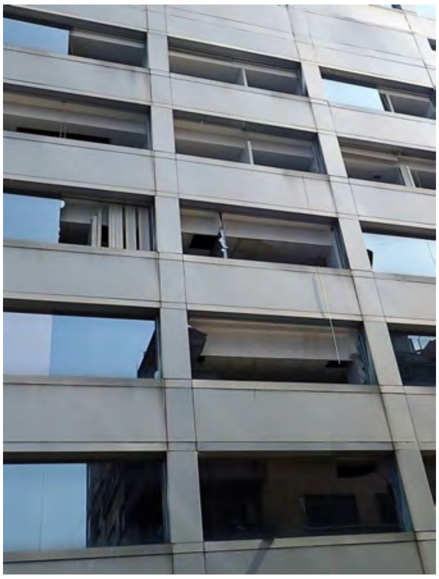


Figure 6 23 - Loss of non-structural glass panels

The following table (**Table 6.1**) displays the frequency of observation for the different pathologies as a function of the number of floors of the building and its main typological class.

Tableau 6.1: Observation frequency of the different damages of the superstructure

Number of floors	1 - 3	3 - 10	10 - 15	> 15
Main building typology	Masonry	Reinforced concrete beams with masonry infill	Reinforced concrete frame with shear panel bracing	Mixed- or steel frame constructions
Destruction of structural elements	Low	Moderate	Low	Not observed
Deterioration of masonry infills	Low	Frequent	Not observed	Not observed
Fall or instability of external, non-structural elements	Low	Low	Low	Low
Building collision	Low	Low	Low	Not observed
Building tilt	Low	Low	Not observed	Not observed
Partial degradation of the soil-structure interface	Not observed	Low	Low	Supposed
Classification scale in terms of frequency of observation: Not observed / Low / Moderate / Frequent				

6.4 Soil dynamic / structure correlation

Observations made in the course of the mission have shown that one specific type of building was particularly susceptible to damage caused by the earthquake under investigation (4- to 8 story buildings with a concrete post and beam frame and masonry infill). Among the possible causes for this, the impact of a double soil / structure resonance phenomenon was regularly mentioned. This effect corresponds to a sympathetic resonance between the soil and the structure, which may occur when the frequency content of the earthquake is particularly rich in the range close to the natural frequencies of both the soil and the structure. The risk is obviously increased if these natural frequencies are themselves close to one another.

This section aims to investigate this issue using measurements of soil frequency performed during the mission on the one hand, and numerical calculations relating to the vibrational behavior of buildings on the other.

6.4.1 Analysis of the measured soil frequencies and of the EC8-estimated building frequencies

The first step in this study of the dynamic soil / structure correlation is to bring together the locations of collapsed or severely damaged buildings with that of the soil frequency measurements carried out during the mission. 17 buildings (14 collapsed and 3 damaged) and 9 measurements (5 in the Condesa – Roma area, and 4 further south) were selected on account of the relative proximity of their locations (Figure 6-24 and 6-25).

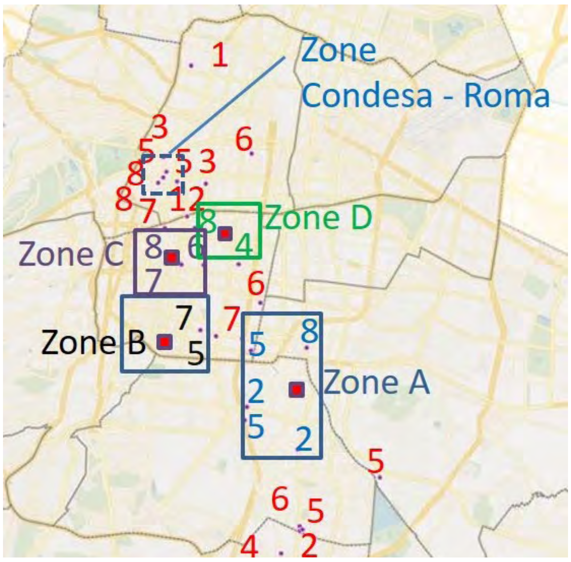


Figure 6-24 - Distribution of collapsed buildings in the central part of Mexico City including H/V measurement zones – the numbers refer to the numbers of floors.

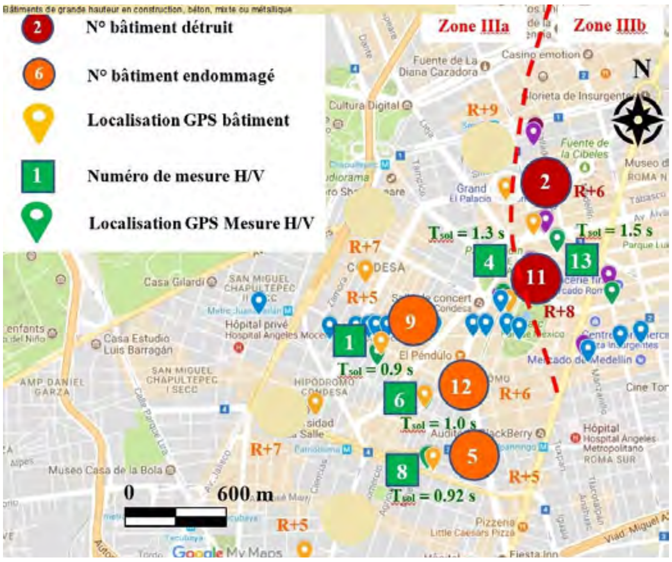


Figure 6-25 - Detail indicating the locations of a selection of collapsed and damaged buildings in the Condesa and Roma Colonias, associated to the H/V measurement points.

In the second step, the natural frequency of the selected buildings is assessed. For concrete framed structures, the Eurocode 8 proposes the following formula: Tbat = 0.075.H3/4, where H is the height of the structure (for H < 40m). Table 6-2 displays the estimated natural period for each of the 17 selected buildings (column 5, with hfloor = 3.5m) and the corresponding soil natural period measurement (column 6). These values are also reported in Figure 6-27 (curve 1 and scatter plot).

Tableau 6.2 : Estimation of natural periods of the selected buildings and corresponding soil measurements

Building location	H/V meas. number	Number of floors	Damaged (D) Collapsed (C)	T_{bat} Period (s) (flexure, acc. EC8)	T_{sol} Period (s) (H/V)	T_{sol} / T_{bat}
Zone A	25	3	C (2 buildings)	~ 0.43	1.36	3.16
Zone D	24	5	C	~ 0.64	1.64	2.56
5	8	6	D	~ 0.73	0.92	1.26
9	1		D		0.92	1.26
Zone B	26		C		1.08	1.47
Zone A	25		C (2 buildings)		1.36	1.86
12	6	7	D	~ 0.82	1.00	1.21
Zone C	27		C		1.23	1.50
2	13		C		1.50	1.83
Zone B	26	8	C	~ 0.91	1.08	1.18
Zone C	27		C		1.23	1.35
Zone C	27	9	C	~ 1.00	1.23	1.23
11	4		C		1.30	1.30
Zone A	25		C		1.36	1.36
Zone D	24		C		1.64	1.64

By comparing the fundamental periods of the buildings (estimated using the EC8 approach) and those of the soil (H/V measurements), we notice that the former are systematically lower than the latter. For buildings of 5 to 8 floors, this discrepancy is between 20 and 250%. Therefore, no soil / structure correlation can be established on the basis of frequency comparison alone. Nonetheless, it should be remembered that the rigidity loss due to damage will increase a building's natural period.

In the following numerical study we will first assess the evolution of building frequencies when damage occurs and then compare these frequencies with their measured soil counterparts.

6.4.2 Numerical analysis of the evolution of building natural frequencies

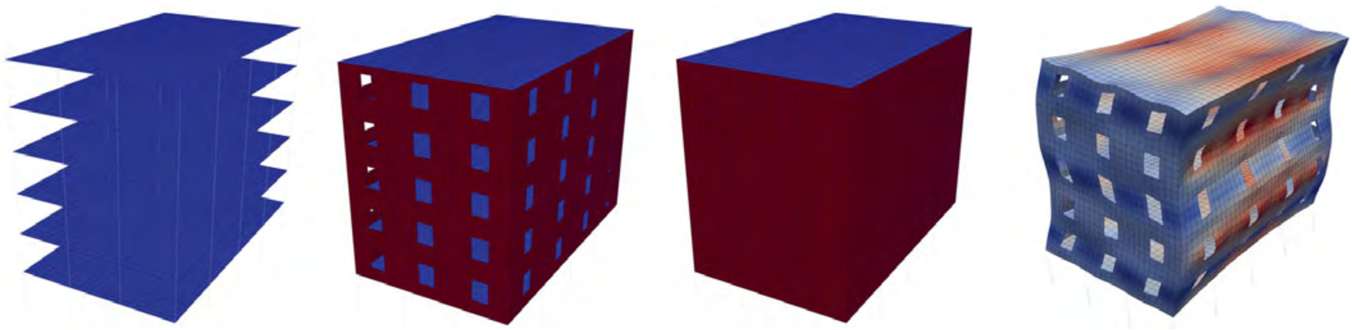
The numerical model that was constructed represents a “typical” structure (and not a particular building) corresponding to the most impacted building typology (Figure 6-26) i.e. a post and beam frame with masonry infill and an “open” ground floor. It is rectangular in plan (12m x 16m), featuring three 4 meter beam spans across its width and four 4 meter beam spans across its length. The floors are 0.15 m thick, and the posts and beams have a 0.25 x 0.25 m2 cross-section. The number of floors can be adjusted. Regarding the masonry walls, three configurations were adopted:

a. without infill, representative of a structure damaged at this level,

b. with infill and with openings (windows),

c. with infill and without openings.

The modelling was performed using Cast3M finite-element software. Beam-type elements (Euler-Bernoulli) were used for the posts and beams whereas shell-type elements (single-layer) were used for the floors and infill walls. Reinforced concrete and masonry were characterized by their Young’s modulus (40 GPa and 20 GPa, respectively), their Poisson’s ratio (0.2 for both) and their density (2,500 kg.m-3 and 2,300 k.m-3, respectively). The posts were assumed to be embedded at the base.



(a) Without infill (b) With infill and openings (c) With infill and no openings (d) Example of modal warping

Figure 6 26 - Numerical model used for the three configurations analyzed

The numerical study involved estimating, for each configuration, the evolution of the fundamental frequency of the structure as a function of the number of floors. The results are presented in Figure 6-27. It can be observed that, under pristine (non-damaged) conditions, the influence of openings is negligible (curves 3 and 4), whereas the absence of infill leads to a period increase by a factor of about 6 (curve 2). We should emphasize the fact that, even though this study reveals the trends, it would have been interesting to extend the analyses to scenarios where only part of the infills is treated as damaged. It would undoubtedly have exposed the impact of induced dissymmetry that could cause torsion effects to appear. In addition, the elastic parameters were selected in an approximate manner and it would be worthwhile refining these values.

Figure 6-27 displays the following:

- the estimate of the natural period of a building in accordance with EC8,
- the estimate of the natural period of a building with or without masonry infills,
- the measured soil period in the vicinity of collapsed- or severely damaged buildings.

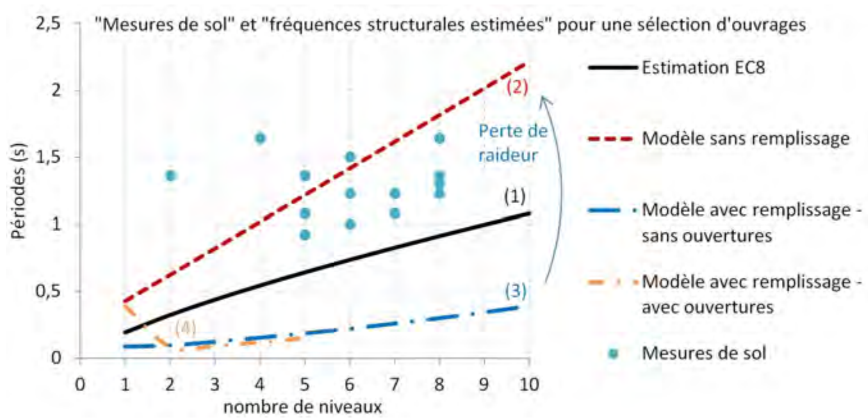


Figure 6 27 - Variations in the fundamental periods of structure and soil for a selection of buildings.

6.4.3 Results and discussion

On account of the idealized boundary conditions, the numerical results displayed in this figure should be regarded as “lower” and “upper” limits for this type of structure. It is, therefore, logical to find that the frequency estimate in accordance with EC8 falls in between these limits.

Regarding the measured soil frequencies, one can see that almost all values fall between the right side of the “EC8” line and the upper limit of the model. During a seismic solicitation, the evolution of damage in the building will tend to force the fundamental periods to depart from the “EC8” value and evolve towards the numerical model upper limit (i.e. without infill).

In such a situation, it is certainly possible that the natural frequency of a building might intercept that of the soil, thus creating a risk of double resonance. In addition, the results clearly show that, for buildings 4 to 8 stories in height, damage to the infill will cause the fundamental period to increase by between 1 and 1.75 s. In reality, this range of periods corresponds to the maximum spectral accelerations observed in the areas where the most severely damaged buildings were recorded.

Therefore, the conditions for the triggering of a double resonance appear to be met and the reality of such a risk cannot be ruled out. Nonetheless, it should be remembered that this phenomenon cannot be regarded as the sole explanation for the damage observed. Indeed, the proximity of similar buildings exhibiting markedly different levels of damage proves that other factors (in particular the capacity of the structural elements) have to be taken into consideration when looking at building damage.

Finally, it must not be forgotten that the present analysis only concerns flexural modes of the structure. Video recordings of the earthquake reveal torsion modes in some structures; damage to infill walls can result in dissymmetries that favor the occurrence of torsion.

6.5 Comparison with the 1985 earthquake

The city of Mexico is subjected to seismic sources of various kinds. Besides earthquake magnitude, epicenter distance and the type of triggering mechanism generate signals that can have very different consequences for structures. Keeping this specificity in mind, a comparison must therefore be drawn between the structural consequences of the September 19th 2017 earthquake and their 1985 counterparts. This section compares elements taken from the AFPS post-earthquake mission of 1985 with observations made in the course of the 2017 mission.

During the September 19th 2017 earthquake the area of maximum damage was located in the geological transition zone: this was also the case for the 1985, 1979 and 1957 events. The Condesa and Roma sector, in particular, was systematically impacted.

By comparing the consequences of the 2017 earthquake with those of the 1985 event, the following points can be made:

- The number of collapsed or severely damaged buildings is significantly lower in 2017 (230 in 2017 versus 878 in 1985).
- In 2017, very few buildings with more than eight floors were affected, whereas in 1985 the buildings that suffered most were between 6 and 15 stories in height. During both events, small buildings (with a low natural period) behaved satisfactorily. These observations can be explained for the most part by the frequency content of the seismic signals. The period corresponding to the maximum accelerations was 1 s in 2017 and 2 s in 1985.
- In 2017, as in 1985, reinforced concrete structures with masonry infill proved the more problematic because of the rapid deterioration of the masonry, which considerably changes the seismic response of the buildings concerned. This issue remains relevant, particularly in the case of buildings predating the 1987 regulations.
- In 2017, as in 1985, it was observed that the more recent the construction period the better the buildings behaved. This demonstrates the advantage of evolutive regulations.
- In 2017 collision between buildings remained a marginal issue, whereas a lot of damage resulted from this phenomenon in 1985.
- Non-structural elements, which had been a major issue in 1985 (fall of glass cladding), behaved very well in 2017. Particular attention had probably been paid to this aspect in the intervening period.

Damage associated with foundation issues, such as tilting or subsidence, was very limited in 2017 but much more significant in 1985. This phenomenon might be explained, in part, by improved zoning and better enforcement, and also by the evolution of the regulatory spectra.

These observations are summarized in Table 6-3.

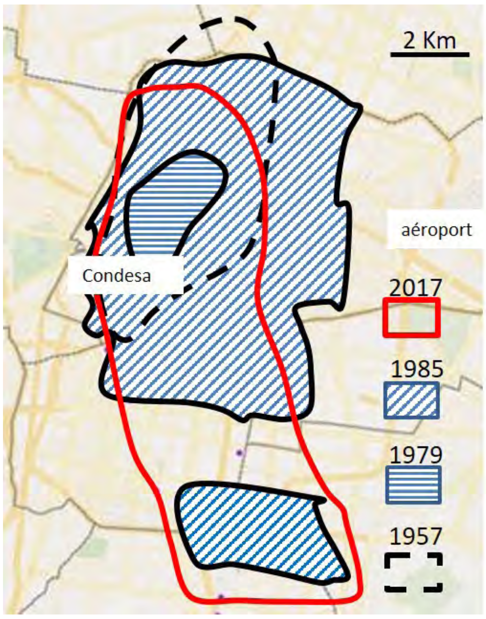


Figure 6 28 - zones of maximum damage

Table 6 -3: Elements of comparison between 2017 and 1985

Observations	2017	1985
Buildings destroyed or put out of use	283	878
Number of stories most impacted	4 - 8	6 - 15
Damage to concrete frame structures with masonry infill	Significant	Significant
Collision between buildings	Contained	Significant
Fall of non-structural elements	Contained	Significant
Tilting or severe damage to the foundations	Contained	Significant
Benefits of evolutive regulations	Evident	Evident

6.6 Main lessons

At the scale of the city, It must be emphasized that the majority of built structures behaved well.

Several issues that had been to the fore in the wake of the 1985 earthquake had only a minor impact in 2017:

- Collisions between buildings and the consequences thereof were uncommon;
- The fall of external non-structural elements such as glass panels, acroteria and balconies was also very limited.

Nevertheless, some aspects remained problematic:

- The behavior of masonry infill walls and their weak resistance to out-of-plane solicitations result in their collapse;
- The loss of these masonry elements modifies the stress distribution across the structure and impacts directly on the adjacent supporting elements. Damage to these supporting elements is therefore linked to abnormal functioning.

Finally, study of the damage reveals a very marked selectivity phenomenon, at three levels:

- On the geological scale of the site, since the damaged buildings are essentially distributed across the soil “transition zone” of Mexico City;
- At the scale of the typology of the buildings; most of the damage recorded was concentrated in buildings consisting of 4 to 8 floors and built using a reinforced concrete post and beam frame with masonry infill;
- Within a given typology, since for similar constructions, often located in very close proximity, some were severely impacted while others did not exhibit any visible damage.

Complementary information

Extracts from Nota Informativa del Grupos de Sismologia e Ingenieria de la UNAM of September 23rd 2017

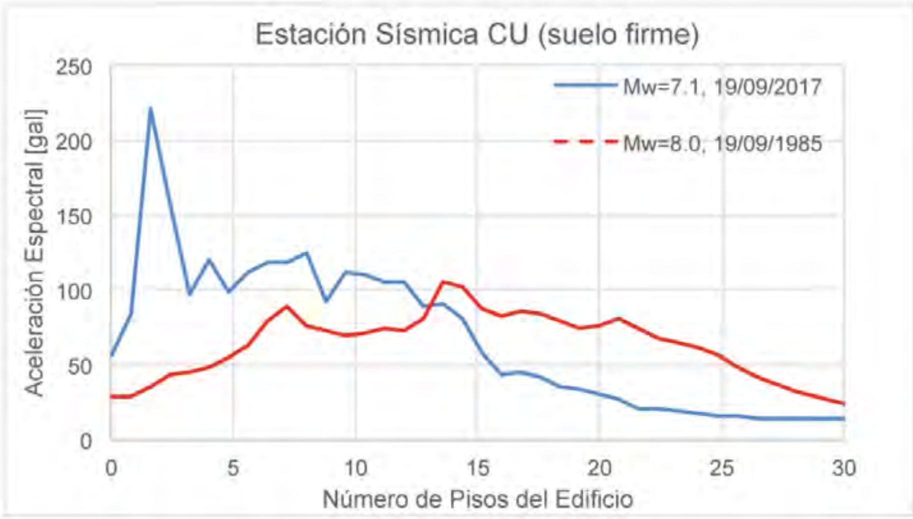


Figure 6 29 - Spectral accelerations as a function of the number of floors for 1985 (red) and 2017 (blue) on hard ground (UNAM 23.09.2017)

Figure 6 30 - Accélération spectrale suivant le nombre d'étage pour 1985 (en rouge) et 2017 (en bleu) sur sol meuble (UNAM 23.09.2017)

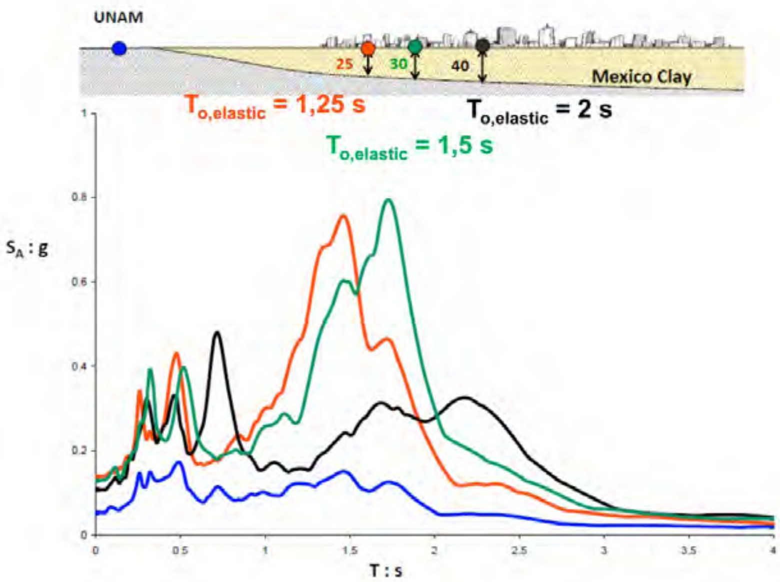


Figure 6 31 - Spectral acceleration depending on building location (NTU 25.09.2017)

7 Retro-fitted buildings

Since 1985, numerous buildings have been the subject of seismic retro-fitting. In the course of our mission, we also encounter retro-fitting works carried out after the September 19th 2017 earthquake. This section presents the different types of reinforcement observed, their operating principle and their behavior following the September 19th 2017 earthquake.

7.1 Regulatory context

In October 1985, following the September 1985 earthquake, Mexican authorities issued an emergency standard applicable to new buildings and buildings to be retro-fitted [1]. In 1987, a complementary standard was introduced which took into account new criteria such as ductility [2]. In 2004, provisions were passed for the rehabilitation of masonry structures. In December 2017, following the September 19th 2017 earthquake, a standard for the rehabilitation of damaged buildings was introduced [3].

7.2 Typologies of retro-fitting solutions observed

During the mission, we came across four types of seismic retro-fitting. Sections 7.2.1 and 7.2.2 present examples of retro-fitting works dating to before and after the September 2017 earthquake.

Reinforced concrete strengthening (Figure 7 1, examples 1, 2 and 3):

This technique involves either increasing the capacity of supporting elements by opting for larger dimensions, or adding new reinforced concrete elements. From the point of view of the dynamic characteristics, this type of strengthening modifies the rigidity and the mass distribution of the structure. We note that this technique was mainly employed for reinforced concrete buildings with between 10 and 20 floors.

Steel brace retro-fitting (Figure 7 2, examples 4, 5, 6, 7, 8 and 11):

This technique involves adding a bracing system to transfer any horizontal stress arising from seismic acceleration downwards to the structure's foundations. The braces are generally made of steel profiles or sometimes take the form of tie rods. This type of retro-fitting was regularly observed on concrete buildings of 5 to 10 floors. The overall rigidity resulting from this type of reinforcement may significantly modify the fundamental frequencies of the buildings concerned.

Strengthening of reinforced concrete elements by attachment of steel plates (Figure 7 3, example 12):

This technique aims at increasing a posteriori the amount of reinforcement in a concrete element. These additions are positioned on the outside of the elements concerned and usually consist of metal plates. This type of strengthening adds resistance and ductility while preserving the dynamic characteristics of the building. The technique was observed on only one building, which was undergoing strengthening works at the time.

Retro-fitting of energy dissipation systems (Figure 7 4, examples 9 and 10):

This technique consists of adding specific elements whose role is to increase energy dissipation in a structure when an earthquake causes it to move. The use of viscoelastic dampers in a rehabilitation context was observed on very high buildings. This technique can control both the dampening and the fundamental frequency of a structure. It should be noted that, in some cases, retro-fitting also involves modification of the initial structure: for instance, floors can be removed or the structure can be subdivided to create several independent units. This results in the modification of the mass distribution and dynamic response of the building.

Figure 7 1 - Strengthening using concrete shear panels

Figure 7 2 - Strengthening using steel braces

Figure 7 3 - Strengthening of concrete elements

Figure 7 4 - Retro-fitting of an energy dissipation system

7.2.1 Examples of buildings retro-fitted prior to the earthquake of September 19th, 2017

Example 1 – Strengthening using reinforced concrete and modification of the original geometry: The Tlatelolco complex

Built between 1960 and 1964, the «Nonoalco Tlatelolco» residential complex symbolic of the concentration of population in Mexico City. During the 1985 earthquake, this district witnessed significant cases of building collapse and a campaign of strengthening works on the reinforced concrete buildings ensued. Figures 7-5 and 7-6 show one building in the complex before and after strengthening.

Figure 7 5 - Building in 1960, before seismic retro-fitting

Figure 7 6 - Building strengthened after 1985

The retro-fitting involved the following:

- Implanting new piles 6.5 m from the façade,
- Dividing the whole structure into substructures by removing some of the gable panels over the full height, so as to shorten the initial structure by 35 cm and to create a 70 cm space between each of the new modules,
- Installing stiffeners over the full height of both principal façades,
- Inserting beams to link the posts on every third floor.

The retro-fitting principle is illustrated in 7-7.

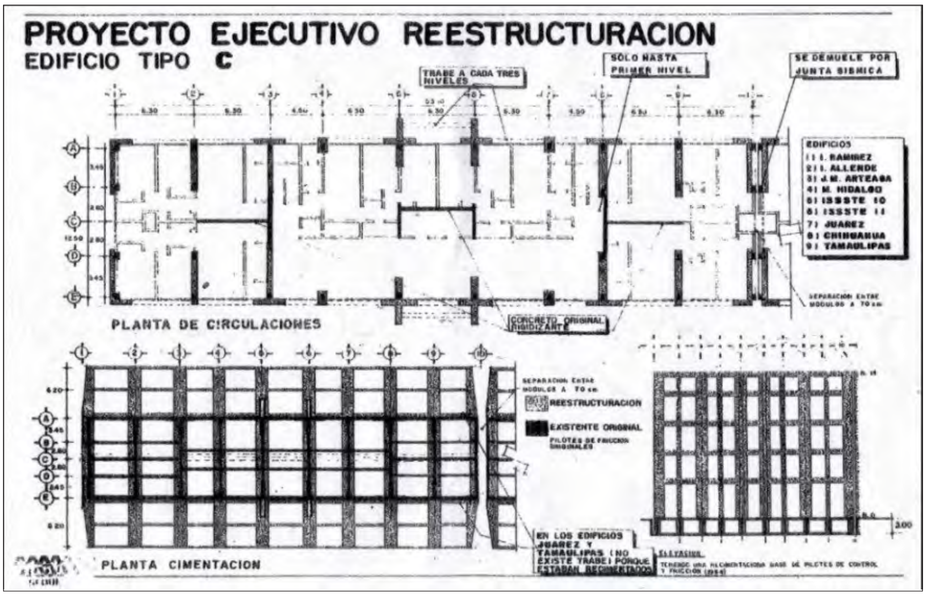


Figure 7 7 - Retro-fitting principle implemented in one of the buildings in the Tlatelolco District – Plan

During the September 19th 2017 earthquake, the building did not incur any visible structural damage, even though it had been subjected to horizontal displacements of approximately 50 cm.

Example 2 – Reinforced concrete strengthening: Buildings in the Tlatelolco complex

In this case we are looking at the strengthening of four buildings built in 1964 and belonging to the same urban complex as the previous example. The buildings, of a type commonly referred to as “tower blocks”, were strengthened by attaching concrete panels to their façades. Figures 7-8 to 7-10 show the two types of strengthening works carried out. It should be noted that these buildings behaved quite well during the September 19th 2017 earthquake.

Figure 7 8 - Retro-fitted buildings, overall view

Figure 7 9 - Full-height orthogonal shear walling

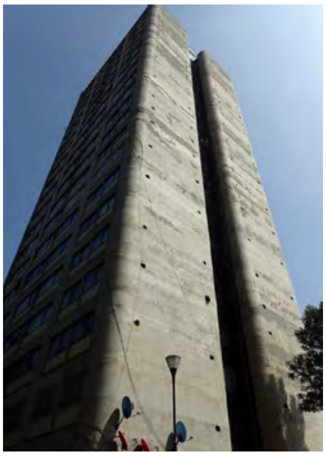


Figure 7 10 - Full-height shear panels

Example 3 - Reinforced concrete strengthening: reinforced concrete post and beam construction with masonry infill

The presence of cross- and V-shaped braces was regularly observed on the façades of buildings constructed using a reinforced concrete post and beam frame with masonry infill (Figure 7-11 and Figure 7-12). It is not always easy to decide whether these braces were installed during the initial construction stage or at a later date.

This type of bracing is also used to consolidate two parts of a single building presenting a potential risk of torsion (Figure 7-12). The buildings fitted with this type of bracing did not exhibit any visible damage, apart from the occasional missing brick.

Figure 7 11 - Bracing on a masonry wall

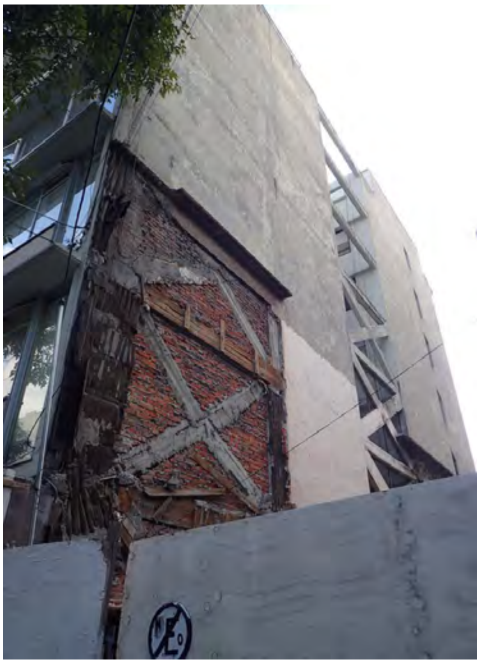


Figure 7 12 - Bracing on a masonry wall and between two buildings

Example 4 - Retro-fitted metal bracing

Figure 7-13 shows a 10 story concrete building located in the Roma district (one of the worst affected areas). It has been strengthened in its entirety using cross bracing mounted on the exterior and also on the interior of the building. This building did not display any visible damage following the September 19th 2017 earthquake.

Figure 7 13 - Cross bracing strengthening – overall view

Figure 7 14 - Detail of the cross-bracing system at ground floor level

Example 5 - Retro-fitted metal bracing

Figure 7-15 and Figure 7-16 show retro-fitting using metal profiles on the façade of the 6 story Ministry of Agriculture building. Apart from increasing the capacity of the building, this type of strengthening also helps to restrict lateral displacements and, consequently, reduces the risk of collision. This building did not display any visible damage following the September 19th 2017 earthquake.

Figure 7 15 - Façade bracing: overalll view

Figure 7 16 - Detail of strengthening at the base of the building

Example 6 - Retro-fitted metal bracing

Figures 7-17 to 7-19 show the retro-fitting works carried out in 1990 at the French Institute of Latin America (IFAL), which comprises several two- and three story buildings.

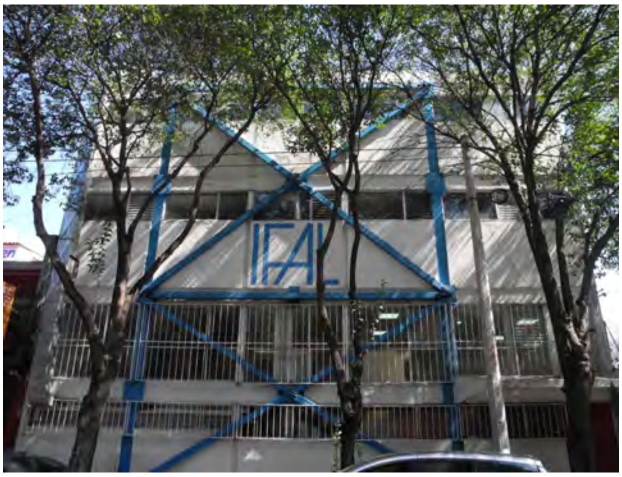


Figure 7 17 - Façade bracing

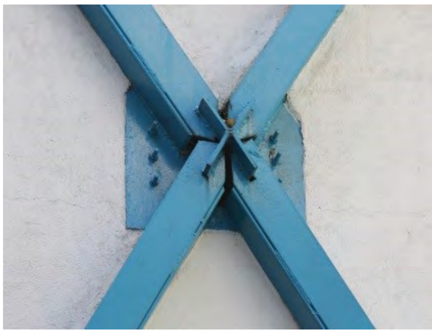


Figure 7 18 - Detail of strengthening system

Figure 7 19 - Detail of strengthening at the base of the building

Example 7 - Retro-fitted metal bracing

Figures 7-20 and 7-21 show a three story building to which a strengthening system has been fitted to the corner. This layout was certainly adopted in order limit the problem of torsion. Through the windows we can get a glimpse of the suspended ceiling is missing many suspended ceiling panels, indicating that the building was subjected to substantial tremors during the September 19th 2017 earthquake. However, it does not display any visible structural damage.

Figure 7 20 - Metal strengthening system at the corner of the building

Figure 7 21 - Metal strengthening system - detail

Exemple 8 - Metallic construction retro-fitted with San Andreas crosses

Figures 7-22 and 7-23 show the retro-fitting works to a building whose bracing system consists of metal tie rods anchored to every fourth floor. This building did not exhibit any visible damage.

Figure 7 22 - Retro-fitting of metal tie rods

Figure 7 23 - Detail of the metal tie rods

Example 9 – Retro-fitted energy dissipation devices

This type of retro-fitting is the subject of a recent standard introduced in December 2017. Therefore, the examples presented here did not fall under any Mexican standard at the time of their installation. The first buildings strengthened using the energy dissipation technique are over 25 years old. No visible damage was noted on the buildings we examined that were strengthened in this manner.

Figures 7-24 and 7-25 show a diagonal, viscoelastic-type strengthening system.

Figure 7 24 - Dissipation systems installed at each floor level

Figure 7 25 - Dissipation system: Detail view of the dampers

Example 10 - Retro-fitted energy dissipation devices

Figure 7-23 and Figure 7-24 show the ongoing strengthening works on the building of the Ministry of the Economy, initiated nearly two years ago. A combination of horizontal stiffeners and diagonal dissipaters has been fitted over the full height of the building. These retrofitted elements are applied to the original reinforced concrete structure. No visible damage was observed on this building.

Figure 7 26 - Full height retro-fitting

Figure 7 27 - Detail view of the diagonal dampers and horizontal stiffeners

7.2.2 Examples of buildings retro-fitted following the 2017 earthquake

Example 11 - Retro-fitted metal bracing

This building, which houses a private medical center, is constructed on a reinforced concrete post and beam frame, with a relatively open ground floor (Figure 7-28). The cross bracing has been applied both outside and inside the building (Figure 2-29), in order to ensure stability at all levels.

Figure 7 28 - Before strengthening

Figure 7 29 - Ongoing retro-fitting works

Example 12 – Strengthening of concrete elements by attachment of steel plates: multistorey car park

A single example of this type was observed. This technique was implemented to strengthen posts at the ground floor level of an eight story car park (Figure 7-30). Steel strapping was used in order to confine these posts and increase their resistance to compression and shear solicitations. A resin (e.g. epoxy) was injected to fill the cracks present in the posts. Furthermore, the strengthened posts are combined with additional posts (Figure 7-31) and shear panels (Figure 7-33), some of which were already present before the 2017 earthquake (visible on photographs dating from 2008).

It is worth noting that this building does not appear to have incurred any major damage following the September 19th 2017 earthquake (it had not been strengthened at the time), even though its height (8 floors) and design, with its significant surface floor mass, should have rendered it vulnerable.

Figure 7 30 - Car park – San Luis Potosi – 8 floors

Figure 7 31 - Strengthened corner post and buttress post

Figure 7 32 - Strengthened post at ground floor level and additional posts

Figure 7 33 - Strengthening of a post

7.3 Main lessons

It is important to emphasize that, at the scale of the city, the buildings retro-fitted using the various techniques presented in this chapter behaved quite well during the September 19th 2017 earthquake. None of the examples we examined exhibited any damage.

It is also interesting to note that each of the strengthening techniques is applied to one particular type of structure. This indicates that local engineers are accustomed to dealing with the issue of strengthening.

References

[1] Norme de Emergencia en Materia de Construcciones para el Distrito Federal.Diario oficial 1985.

[2] Normes Tecnicas complementarias para diseno sismico 1987.

[3] Normas para la rehabilitacion sismica de edificios de concreto danados por le sismo del 19 de septiembre de 2017.

8 Public utility networks

This chapter takes a look at the networks damaged during the September 19th 2017 earthquake.

Figure 8-1 – Mexican states with networks damaged by the 2017 earthquake (Wikipedia document).

8.1 Telecommunications networks

A survey of damaged telecommunication sites is presented in Table 4. There are no available data for the adjacent state of Puebla.

City or State	Number of damaged sites
Mexico City (CDMX)	93
State of Mexico (EDOMEX)	44
State of Morelos	7

Table 4. Telecommunication sites damaged in Mexico City, the state of Mexico and the state of Morelos.

The telephone cable network incurred some damage during the earthquake, while mobile and internet services remained virtually uninterrupted (except for saturation events caused by the huge number of simultaneous connections)..

A statement released by the Instituto Federal de Telecomunicaciones indicates that the public telecommunications networks were 98 % operational within 72 hours after the earthquake.

We also note that access to free mobile telephone services was provided to rescue teams.

8.2 Transport networks

Highways and Bridges

The Pirámides highway construction site sustained some damage with the collapse of a bridge under construction in Texcoco (State of Mexico).

In Chimalhucán, a road bridge was damaged, but the extent of the damage is not known.

In the state of Morelos, a bridge collapsed on the Mexico-Acapulco highway, at km 109.

A bridge collapsed in Ixtaltepec, in Oaxaca State (No details given as to whether the collapse was caused by the September 7th earthquake or by the September 19th earthquake).

La Unión Bridge collapsed in Villa Corzo, Chiapas State (No details obtained as to whether the collapse was caused by the September 7th earthquake or by the September 19th earthquake).

Metro network

It was reported to the mission that the Mexico City metro service operated normally and did not sustain damage.

8.3 Power and water networks

Following the earthquake, the emergency response outlined in a statement by the President of the Republic included vital networks as part of the first contingency measures, on an equal footing with social services:

- Social security,
- ISSSTE (Instituto de Seguridad y Servicios Sociales de los Trabajadores del Estado),
- PEMEX (old national oil company, which has lost its monopoly but retains a solid local presence across the territory),
- National Defence Secretariat,
- Naval Secretariat.

Electricity

As a safety measure, the electricity supply was deliberately cut in all the impacted areas immediately following the earthquake, and then restored within minutes.

It was reported that a number of transformers fell in the state of Mexico (Ecatepec, Xalostoc industrial estate). Some CFE (Comisión Federal de Electricidad) substations were damaged in the state of Morelos.

Windfarms were impacted in the states of Oaxaca and Chiapas (probably by the September 7th earthquake). The managers of these farms worked hand in hand with CFE and CENACE (Centro de Control de la Energía) to restore the supply of electricity to the national grid. There are no reports of falling windturbines or aerogenerators.

Water

On its website, The Comisión Estatal del Agua of the state of Oaxaca (CEA Oxaca) featured several repair works carried out in the wake of September 7th earthquake and its aftershocks. This made it possible to monitor the restoration of services in real-time. Judging from online photographs, we can see that repair works were carried out under conditions far from the usual operational practices (non-secured excavations, variable wearing of safety equipment, etc.). The repair team interventions were prompt. The techniques employed (identified on the basis of the photographs) often involved the replacement of a section of metal pipe by a non-metal pipe (it is difficult to determine whether replacements are made of polyethylene, PVC, or composite, etc.). Metal-plastic connectors are also used.

We were not able to obtain overall figures for leakage volumes and service interruption times following stoppages of well pumps.

Figure 8.2 – (Pipe repair works in Ixtaltepoec (Oaxaca). (Right) Road collapse in Tlahuac (CDMX) due to a damaged water pipe.

The most impacted water networks in Mexico City (CDMX) were located in the Delegaciones Iztapalapa and Tlahuac. Several leaks had to be repaired. The collapse of a road is also reported, where an underground pipe burst causing the soil to move.

6 instances of leakage and 7 damaged wells were reported for the state of Mexico. In the state of Morelos, 17 water pipes were damaged.

Oil and Gas

Except for a leak in a 2-inch steel gas distribution pipeline located in the epicenter area (operating pressure not communicated), no damage was reported for the gas and liquid hydrocarbon transport and distribution networks.

The Los Ramones pipeline, located north-west of Mexico City, is fitted with a buried optical fiber running alongside it, mainly for third-party detection. During the September 7th earthquake, this system recorded the seismic tremors.

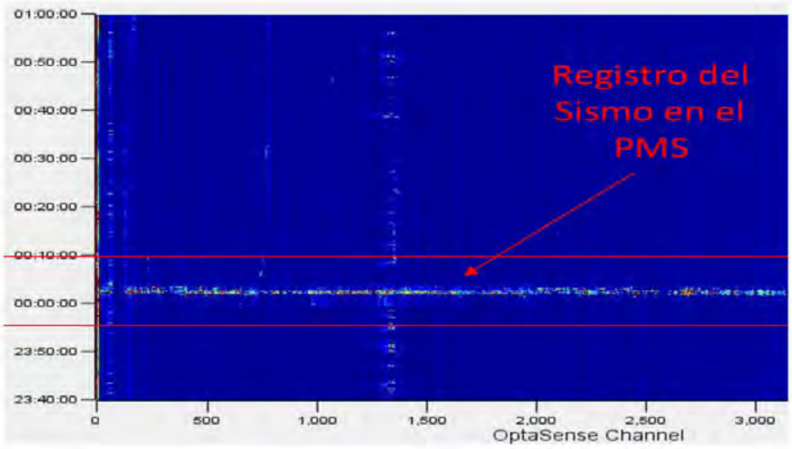


Figure 8.3 – Gas transport pipeline fitted with fiber optic cable

8.4 Other infrastructure

Toppling of equipment was recorded in a pharmaceutical plant in Mexico State (Ecatzingo industrial zone).

It was not possible to visit industrial sites as part of the mission; however, we received reports that a refinery to the north of Mexico City witnessed significant movement of equipment without suffering any actual damage.

Similarly, on a methane production site in Tamaulipas State (relatively far from the epicenter) no particular damage was recorded.

There was no recorded damage to off-shore installations.

8.5 Main lessons

Having compared the above conclusions with those of the 1985 mission report, it appears that findings regarding networks are quite similar and indicate that industrial installations withstood the earthquake very well.

The hydrocarbon transport and distribution networks also behaved very adequately, which is coherent with the feedback generally gathered from major recent earthquakes (Izmit 1999, Tohoku 2011).

The water distribution pipes, however, caused some damage which is likely to have had an impact on the roll-out of rescue operations, and it should be noted that restrictions on the consumption of drinking water were still in place 2 months after the earthquake.

As in 1985, the transport networks, and in particular the metro system, behaved very satisfactorily, as did the telecommunications networks which greatly contributed to the good organization of rescue operations following the earthquake.

Electricity supply was intentionally shut down, but was restored very rapidly, which testifies to the attention paid by the Mexican authorities to the anti-seismic industrial design outlined in the guide edited by the local national electricity company, la Compañía Federal de Electricidad.

9 Emergency simulation drill

9.1 Nature of the drill

Since 1985, «el simulacro» (the "Simulation) takes place every 19th September in Mexico City. In reality, this is an evacuation and crisis management exercise in case of an earthquake. It is a yearly event which is taken very seriously. It is planned, announced in the press and in the media, and is the subject of a very detailed evaluation. In 2017, the media referred to the exercise as «macrosimulacro» and even «megasimulacro» in a bid to encourage the public to take part.

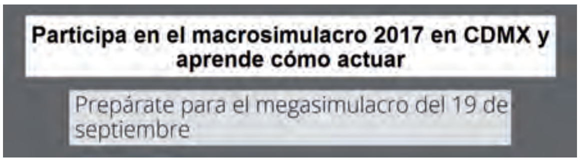


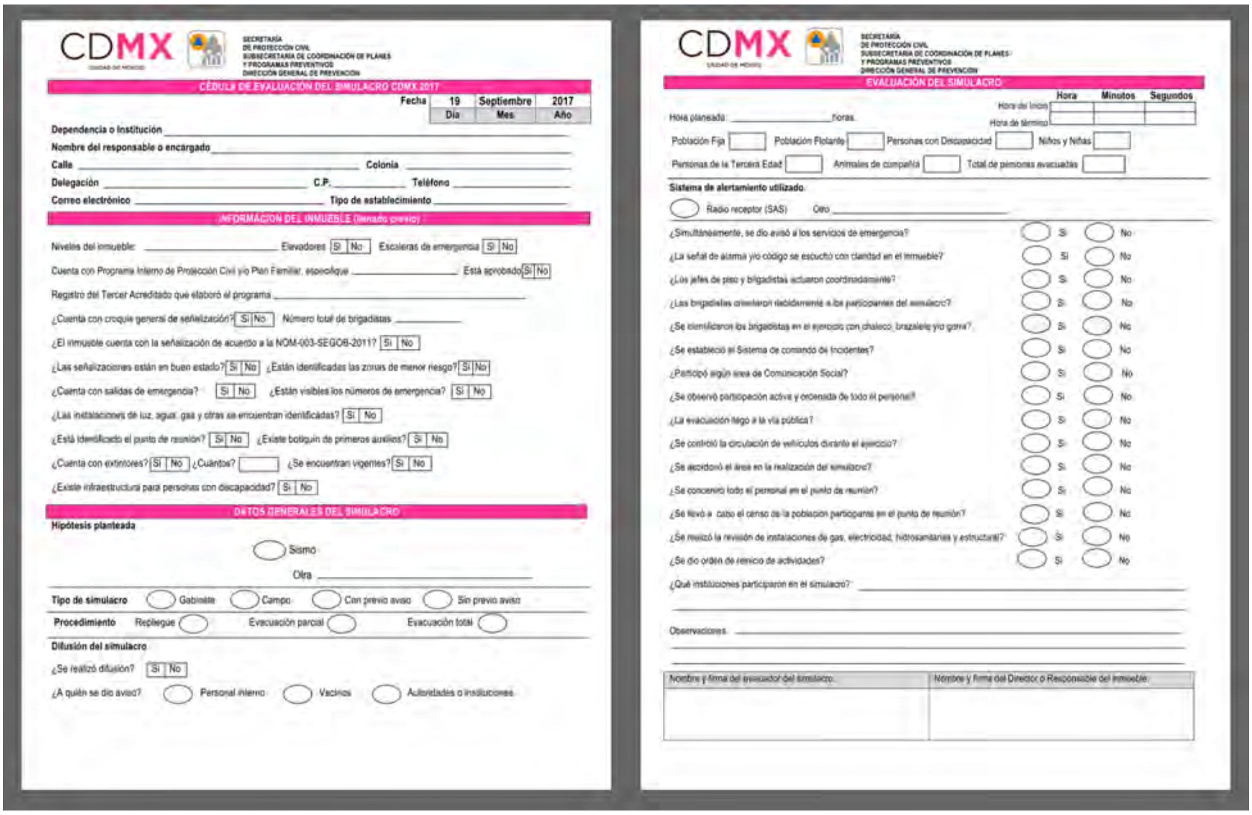
Figure 9.1 – « Macrosimulacro» and «megasimulacro» in the media

As part of the preparation for the drill, the procedural guide of the Civil Protection stipulates five points to be observed:

1. Register the property and obtain a registration number
2. Hold a preliminary meeting with the internal committee in charge of security, working on the hypothesis of an evacuation within 40 s of the alarm
3. Carry out the drill on September 19th 2017 at 11h00 on the triggering of the SAS (Seismic Alarm System) alarm sirens
4. Issue the return order and proceed immediately with the drill assessment meeting
5. Fill in the assessment form as soon as possible and send it to the Civil Protection Secretariat in order to obtain an attestation of participation

The evacuation instructions are as follows:

- People residing at ground floor and first floor levels evacuate towards the assembly points if they fall within the 40 s deadline zone
- People living on the second floor and upper or residing outside the 40 s range withdraw into areas deemed less risky and only evacuate towards the assembly points once the earthquake is over
- Following evacuation, counting is carried out by the persons in charge at the assembly points
- The drill officer initiates the inspection of the property in order to verify that it is safe to return



CDMX
SECRETARÍA DE PROTECCIÓN CIVIL
SUBSECRETARÍA DE COORDINACIÓN DE PLANES Y PROGRAMAS PREVENTIVOS
DIRECCIÓN GENERAL DE PREVENCIÓN

CÉDULA DE EVALUACIÓN DEL SIMULACRO CDMX 2017

Fecha	19	Septiembre	2017
	Día	Mes	Año

Dependencia o Institución ____
Nombre del responsable o encargado ____
Calle ____ Colonia ____
Delegación ____ C.P. ____ Teléfono ____
Correo electrónico ____ Tipo de establecimiento ____

INFORMACIÓN DEL INMUEBLE (llenado previo)

Niveles del inmueble: ____ Elevadores Sí No Escaleras de emergencia Sí No
Cuenta con Programa Interno de Protección Civil y/o Plan Familiar, especifique ____ Está aprobado Sí No
Registro del Tercer Acreditado que elaboró el programa ____
¿Cuenta con croquis general de señalización? Sí No Número total de brigadistas ____
¿El inmueble cuenta con la señalización de acuerdo a la NOM-003-SEGOB-2011? Sí No
¿Las señalizaciones están en buen estado? Sí No ¿Están identificadas las zonas de menor riesgo? Sí No
¿Cuenta con salidas de emergencia? Sí No ¿Están visibles los números de emergencia? Sí No
¿Las instalaciones de luz, agua, gas y otras se encuentran identificadas? Sí No
¿Está identificado el punto de reunión? Sí No ¿Existe botiquín de primeros auxilios? Sí No
¿Cuenta con extintores? Sí No ¿Cuántos? ____ ¿Se encuentran vigentes? Sí No
¿Existe infraestructura para personas con discapacidad? Sí No

DATOS GENERALES DEL SIMULACRO

Hipótesis planteada
Sismo
Otra ____
Tipo de simulacro: Gabinete / Campo / Con previo aviso / Sin previo aviso
Procedimiento: Repliegue / Evacuación parcial / Evacuación total
Difusión del simulacro
¿Se realizó difusión? Sí No
¿A quién se dio aviso? Personal interno / Vecinos / Autoridades o instituciones

CDMX
SECRETARÍA DE PROTECCIÓN CIVIL
SUBSECRETARÍA DE COORDINACIÓN DE PLANES Y PROGRAMAS PREVENTIVOS
DIRECCIÓN GENERAL DE PREVENCIÓN

EVALUACIÓN DEL SIMULACRO

Hora planeada: ____ horas.

	Hora	Minutos	Segundos
Hora de inicio			
Hora de término			

Población Fija ____ Población Flotante ____ Personas con Discapacidad ____ Niños y Niñas ____
Personas de la Tercera Edad ____ Animales de compañía ____ Total de personas evacuadas ____

Sistema de alertamiento utilizado
Radio receptor (SAS) Otro ____

¿Simultáneamente, se dio aviso a los servicios de emergencia? Sí No
¿La señal de alarma y/o código se escuchó con claridad en el inmueble? Sí No
¿Los jefes de piso y brigadistas actuaron coordinadamente? Sí No
¿Los brigadistas orientaron debidamente a los participantes del simulacro? Sí No
¿Se identificaron los brigadistas en el ejercicio con chaleco, brazalete y/o gorra? Sí No
¿Se estableció el Sistema de comando de Incidentes? Sí No
¿Participó algún área de Comunicación Social? Sí No
¿Se observó participación activa y ordenada de todo el personal? Sí No
¿La evacuación llegó a la vía pública? Sí No
¿Se controló la circulación de vehículos durante el ejercicio? Sí No
¿Se acordonó el área en la realización del simulacro? Sí No
¿Se concentró todo el personal en el punto de reunión? Sí No
¿Se llevó a cabo el censo de la población participante en el punto de reunión? Sí No
¿Se realizó la revisión de instalaciones de gas, electricidad, hidrosanitarias y estructural? Sí No
¿Se dio orden de reinicio de actividades? Sí No
¿Qué instituciones participaron en el simulacro? ____
Observaciones ____

Nombre y firma del evaluador del simulacro.	Nombre y firma del Director o Responsable del inmueble.

Figure 9.2 – «Simulacro 2017» assessment form

Figure 9.3 – Pictures of the «Simulacro 2017»

At 11:00 on September 19th 2017, the alarm is triggered. Evacuations proceed, counting is carried out, buildings are inspected and the people are authorized to return.

Images of the ongoing drill are available on-line almost in real-time.

At 12:21 the head of government, Miguel Angel Mancera, and his team meet to assess the 2017 exercise.

At 13:34, the “real” earthquake strikes.

Mancera analiza resultado del simulacro 2017 en la CDMX

El mandatario capitalino y su gabinete se ubicaron en el cuarto de crisis del C5 para evaluar el número de personas y edificios que participaron en este evento

19/09/2017 | 12:21 | **Sandra Hernández** [Ciudad de México]

El jefe de Gobierno, Miguel Ángel Mancera, y su equipo se reúnen en el **C5** de la **Ciudad de México** para evaluar el **Simulacro 2017**.

Desde hace más de 50 minutos, el mandatario capitalino y miembros de su gabinete se ubicaron en el **cuarto de crisis** para evaluar el número de personas y edificios que participaron en este simulacro.

Mientras tanto, las **cámaras del C5** enfocan diversas calles de la ciudad para monitorear en tiempo real el ejercicio de **protección civil.**

Figure 9.4 – At 12;21 on September 19th 2017,M.A. Mancera and his team met to assess the «Simulacro 2017» exercise

9.2 Main lessons

We were able to observe this annual large-scale exercise has a two-fold benefit:

- By involving most of the population, it helps everyone to react appropriately in the event of a real earthquake
- Above all, it maintains awareness of earthquake risk

For officials and developers alike, the pedagogical benefit is very significant: Indeed, when people take part in a simulation exercise of this scale every year, it seems unlikely that the seismic risks will be forgotten or ignored when commissioning, designing, constructing or managing a building.

In France, we carry out this type of exercise for fire risk, especially in schools where an evacuation drill is organized each year. In general we can say that this risk is not overlooked by officials and developers.

Our so-called «Richter» exercises are intended to address seismic risks. Initially they were mainly intended for security officials (the first «Richter» exercise for instance was simply a desktop exercise). However, as part of the «EU Richter Caraïbes 2017» exercise, on the occasion of the “virtual” earthquake at ten o’clock on Tuesday March 21st 2017 at, schools conducted evacuation drills and the airport was evacuated as were some businesses that had opted to take part.

With the Mexican experience in mind, we strongly recommend that our «Richter» exercises be continued and amplified so that they might eventually match the scale and frequency of the «Simulacro».

10 Crisis management

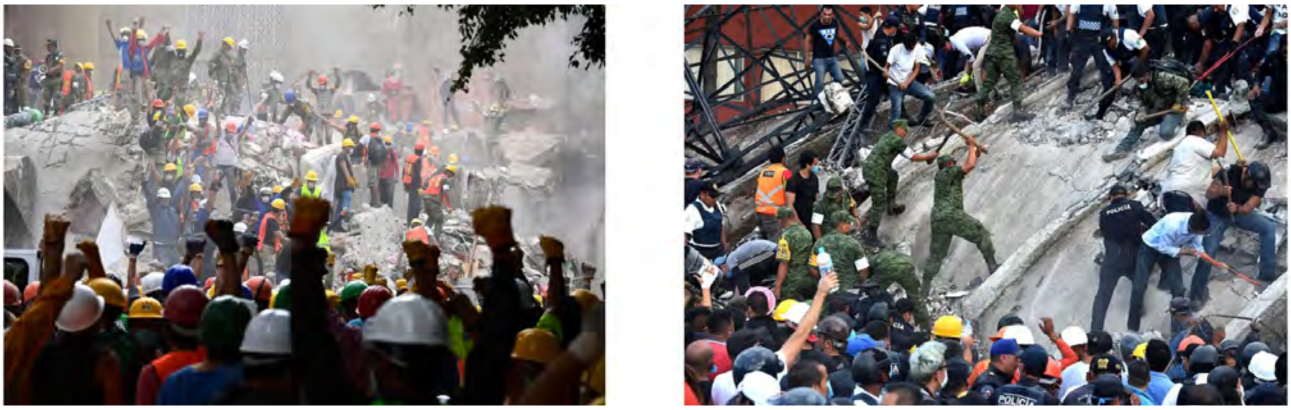


Figure 10.1 – Rescue teams in action (photo:Mexico City AFP office)

10.1 Crisis management protocol

The crisis management protocol is applied on a nation-wide scale since 2014. The Mexican United-States is a federation of 32 states, each possessing some degree of autonomy regarding crisis management. Nevertheless, all states must follow the national guidelines.

In 2014, the national government introduced the **MX** national plan for crisis management which links all of the agencies involved (federal and otherwise):

- Secretaría de la Defensa Nacional (SEDENA): Ministry of Defense,
- Secretaría de la Marina (SEMAR): National Navy,
- Sistema Nacional de Protección Civil (SINAPROC): Civil Protection,
- Petróleos Mexicanos (PEMEX): historic national oil company,
- Comisión Federal de Electricidad (CFE): historic national electricity company,
- Comisión Nacional de AGUA (CONAGUA): National water commission.

Local government has provided the 16 Delegaciones (districts) of Mexico City with an emergency plan. This plan is divided into six operational procedures (Damage identification, etc.) and three support procedures (supplies, etc.) which are detailed in the appendix. Figure 10-2 shows a website made available to the rescue teams by the CENAPRED (Centro Nacional de Prevención de los Desastres) where collapsed buildings are georeferenced with pictures.

Figure 10.2 – Mapping of collapsed buildings with pictures (©CENAPRED)

In the wake of an event, the various agencies rally in order to ensure the emergency rehabilitation of access roads, health services and public utility networks (water, power and telecommunications). Public lighting, transport (road-, railway-, air- and maritime transport), hospitals, schools, housing, public buildings and all other strategic installations also fall within the scope of this plan.

10.2 Unfolding of events

As soon as the earthquake is detected ([SEGOB, 2017]),

- The President of the Republic activates the MX plan and declares that the following three steps will be implemented:
    1. Provision of food and medicine; restoration of the water-, gas- and electricity services.
    2. Surveying of damaged structures and demolition of the more dangerous buildings.
    3. Removal of rubble so as to allow reconstruction works to proceed.
- Following the President's orders, the Executive Management of the Civil Protection (DGPC) appoints a National Emergency Committee (CNU).
- The CNU supervises the support efforts in the states impacted by the disaster and ensures a link between the local authorities and the 6 major federal agencies (see § 10.1):
    - Video coverage from 15,000 video cameras in Mexico City and its environs, operated by the Data control, Communication and Citizen Command Center, is made available to Civil Protection personnel.
    - Rescue teams are sent to the collapsed buildings in order to save as many victims as possible from the rubble.
    - Emergency diagnostics are initiated in accordance with the procedure put in place by the local government of Mexico City (See Figure 10-3).
        1. A request is made via internet or by phone.
        2. A brigada (team) composed of brigadistas (Engineers, architects and construction managing directors) examines the structure and delivers a diagnostic (See § 11 Emergency diagnostics).
        3. Depending on the diagnosis, supplementary verifications are carried out.

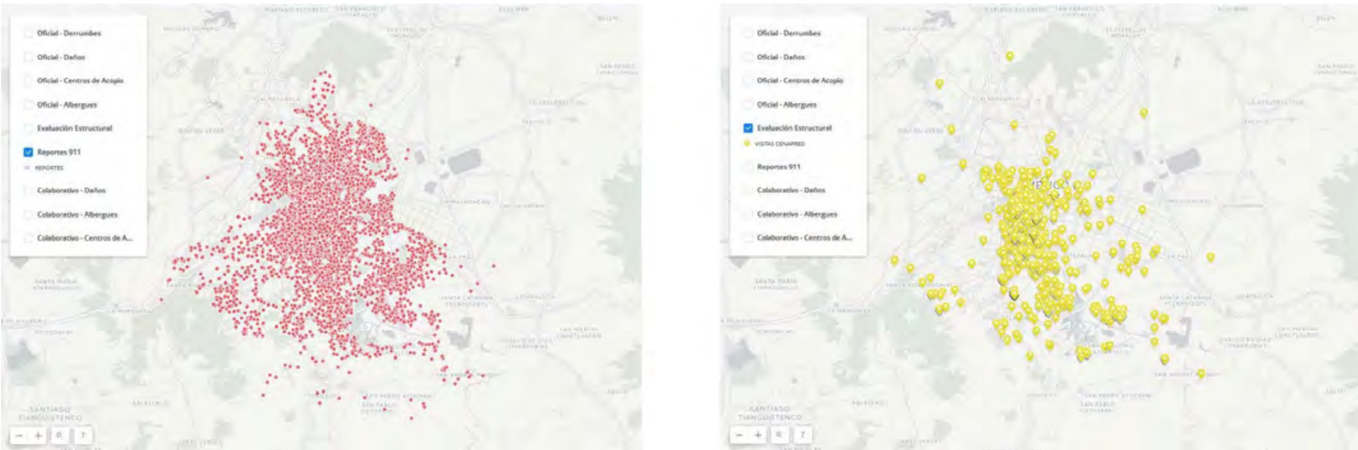


Figure 10.3 – Collaborative use of the Civil Protection internet site to localize 911 calls (red dots, left) and the diagnostics carried out (yellow dots, right)

Two days after the earthquake, 230 deaths and 44 collapsed buildings have been reported in Mexico City. The medical services have treated 1,372 injured persons.

The Comisión Federal de Electricidad indicates that 92 % of the 4.84 million people impacted by power cuts have had their electricity supply restored within 24 hours after the earthquake.

Five days after the earthquake, more than two-thirds of the 11,200 demands for building assessments have been categorized as follows:

6 640 « green » - 688 « yellow » - 321 « red »

On the morning of October 4th, the Civil Protection national coordinator declares that the body of the last missing victim has been found. Officially, 369 people have lost their lives as a direct consequence of the earthquake: 228 in Mexico City, 74 in the state of Morelos, 45 in the state of Puebla, 15 in the state of Mexico, 6 in the state of Guerrero, and 1 in the state of Oaxaca ([URESTE, 2017]).

10.3 Operational organization

- Article 17 of the Civil Protection law determines local responsibilities regarding organization of Civil Protection (running and funding). In the context of earthquakes, Civil Protection officers work in close collaboration with the following organizations:
- The Centro Nacional de Prevención de los Desastres (CENAPRED) whose activities include providing support to the SINAPROC (see §10.1). In effect the CENAPRED is involved in research, training, instrumentation (18 accelerometric stations) and dissemination of information on natural risks, and seismic risks in particular.
- The Centro de Instrumentación y Registro Sísmico (CIRES) which developed the Sistema de Alerta Sísmica (SAS), was founded in 1991 and made a public service in 1993. The SAS links the coastline of Guerrero State to Mexico City in approximately 50 s (times of up to 70 s have been recorded). Two types of alarm are activated depending on the seriousness of the earthquake:
  - Preventive alarm,
  - Public alarm, in general for earthquakes with a magnitude greater than Mw 6.
- The Servicio Sismológico Nacional (SSN) of the UNAM operates approximately one hundred accelerometric stations. Thanks to this network, and also to its own digital resources, the Instituto de Ingeniería is capable of generating intensity maps within a few minutes of an earthquake occurring.

Figure 10.4 – Posters produced by the Servicio Sismológico Nacional (SSN) of the UNAM

10.4 Main lessons

The personnel in charge of managing the 2017 crisis had tools at their disposal that did not exist in 1985 or 1999.

In this regard, we must mention the creation in 2014 of a national coordination plan and the putting in place of modern tools for coordinating operations.

It is also interesting to note that a number of tools that were not initially designed to assist in crisis management (such as the real-time survey of real estate sales/rentals) were diverted from their intended original use in order to optimize the rescue operations.

Neither should we ignore the immediate mobilization of volunteers who rushed to provide first aid, helped with re-housing and later took part in diagnostic operations.

The main lessons to be learnt from this Mexican experience are the importance of both a structured organizational response and a massive spontaneous mobilization of personnel. These two aspects went hand in hand in Mexico City and it is hoped that they will be further developed in France.

References

[SEGOB, 2017] Secretaría de Gobernación (2017). Reporte de acciones de la Coordinación Nacional de Protección Civil, tras el sismo del 19 de septiembre. Mexique : GOB. https://www.gob.mx/segob/prensa/reporte-de-acciones-de-la-coordinacion-nacional-de-proteccion-civil-tras-el-sismo-del-19-de-septiembre (consultation janvier 2018).

[URESTE, 2017] Ureste M., Aroche A. (2017). Lo que el #19S nos dejó: las víctimas, daños y damnificados en México. Mexique : Annimal Político. http://www.animalpolitico.com/2017/10/cifras-oficiales-sismo-19s/ (consultation janvier 2018).

11 Emergency diagnostics

Following a major earthquake, it is essential that emergency diagnostic assessments be carried on structures. The objective is to provide a rapid classification of the structures into simple categories (e.g. usable, temporary supervised access allowed, access forbidden). The idea is to prevent any unnecessary risk to the public and to improve the management of operational and emergency structures by the authorities. These assessments must be carried out as soon as possible after the event.

The information presented in this section arose from our exchanges with Civil Security officials in the city of Puebla, Mexico City's Casa del Arquitecto, the French embassy in Mexico, the local France Presse agency, as well as from the accounts of local residents.

11.1 Organization of the assessments

In Mexico City, the Civil Security had responsibility for the emergency assessment of public buildings. As regards the assessment of private housing, in the absence of any specific initial measures, it was conducted – when at all – in two ways:

First, numerous assessments were carried out at the demand of property owners and tenants by independent engineers, who were, in principle, trained and accredited for this type of intervention. However, these were billed services. As a result of this rather ad hoc approach, in some cases several assessments were carried out for the same structure, sometimes with contradictory conclusions. It should also be noted that there were major discrepancies in the prices charged for these services: we were quoted rates that ranged from €100 to the equivalent of €5,000 euros. Admittedly the sizes of buildings vary, but such was the degree of discrepancy that on September 23rd 2017 the government decided to set a maximum rate for the assessment of schools.

Second, confronted with the significant number of buildings to be examined, the Mexico City Council of Architects decided of its own initiative to organize a program of emergency diagnostics of private buildings. The strategy put in place involved the fast-track training of a maximum number of volunteers in order to answer the demands of members of the public contacting the organization. Therefore, fast-track training of inspectors was provided and teams of two were formed comprised of an experienced, knowledgeable member of staff and a trainee volunteer (a student at the school of architecture). These training sessions, dispensed over an hour in the field, allowed 7,000 volunteers to be trained and approximately 14,000 diagnostic assessments to be carried out free of charge.

Figure 11.1 – Training of volunteers at the Casa del Arquitecto in Mexico City

In the town of Puebla, close to the epicenter, emergency diagnostic operations, including of private and historic buildings, were carried out by the local Civil Security personnel. Thus, the organization of the diagnostics differs between the capital cities of the two different states.

11.2 Nature and methodology of assessments

We were able to examine several evaluation sheets ("Dictamen"). Sometimes these sheets are specific to the engineering firms who carried out the diagnostic assessments; others bear the stamp of the «Civil Protection» (Figure 11.3). All are more or less organized in a similar way, which allows harmonized assessments to be rapidly established by following the steps outlined below.

Step 1: Location and description of the building

This section specifies the address, location and use of the building and whether the examination concerns the exterior or the exterior and interior of the structure.

Step 2: State of the building

This step aims to identify the presence of damage to the structure of the building, or to its service networks and foundations. The main criteria are listed in the table below. For each type of damage listed, the inspector indicates whether it has been observed, is absent or whether there is an element of uncertainty regarding its presence.

Table 11 1: Assessment criteria for assessing the state of a building

	Yes	No	Uncertain
a. Total collapse			
b. Partial collapse			
c. Structure separated from its foundations			
d. Differential or significant subsidence			
e. Visible tilting of the building or a story			
f. Damage to structural elements (posts, beams, walls)			
g. Severe damage to non-structural elements			
h. Damage to electrical installations			
i. Damage to plumbing installations			
j. Damage to gas installations			
k. Ground movement or cracks			
l. Landslide			
m. Parapets, balconies or other elements in danger of falling			
n. Other hazards (severed cables, burst pipes, toxic spills, etc.)			

Step 3: Overall classification

The building is classified into one of four categories, depending on the positive answers obtained during the previous step. It can be seen that the notion of risk is clearly linked to the diagnostics established.

- No positive answer: Safe/low risk building or area
- At least one positive answer to criteria "a" to "f": Unsafe/high risk building
- At least one positive answer to criteria "g" to "n": Unsafe/high risk area
- In case of uncertainty: undetermined level of safety

Step 4: Recommendations

This last step specifies whether or not the building requires a detailed inspection and whether clearance equipment or a specialized intervention are necessary (Civil Protection, water services, engineering services, etc.).

A comment area is also present to receive the evaluation verdict.

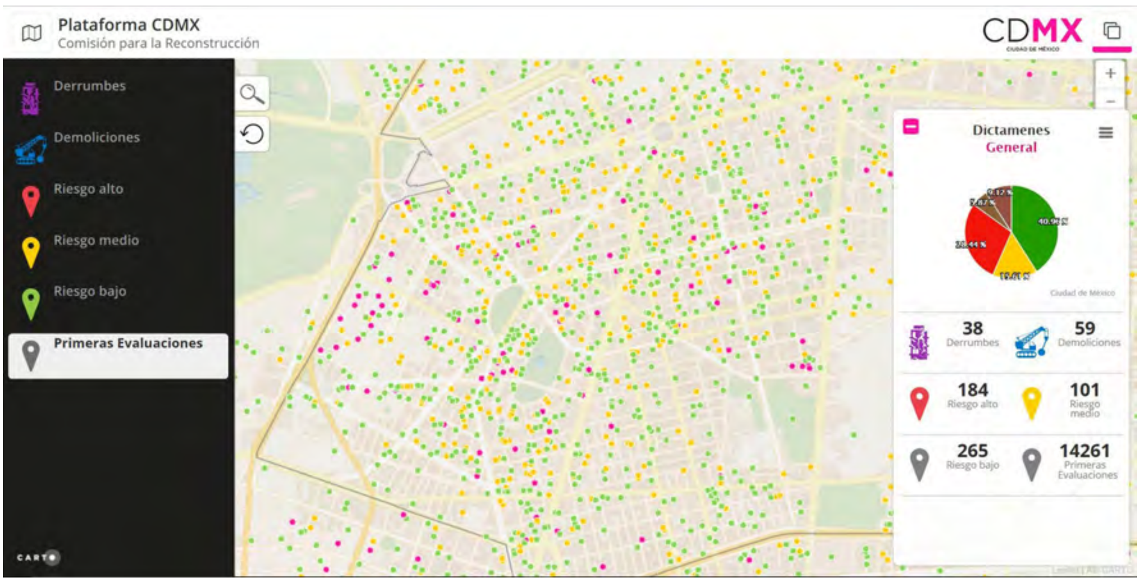
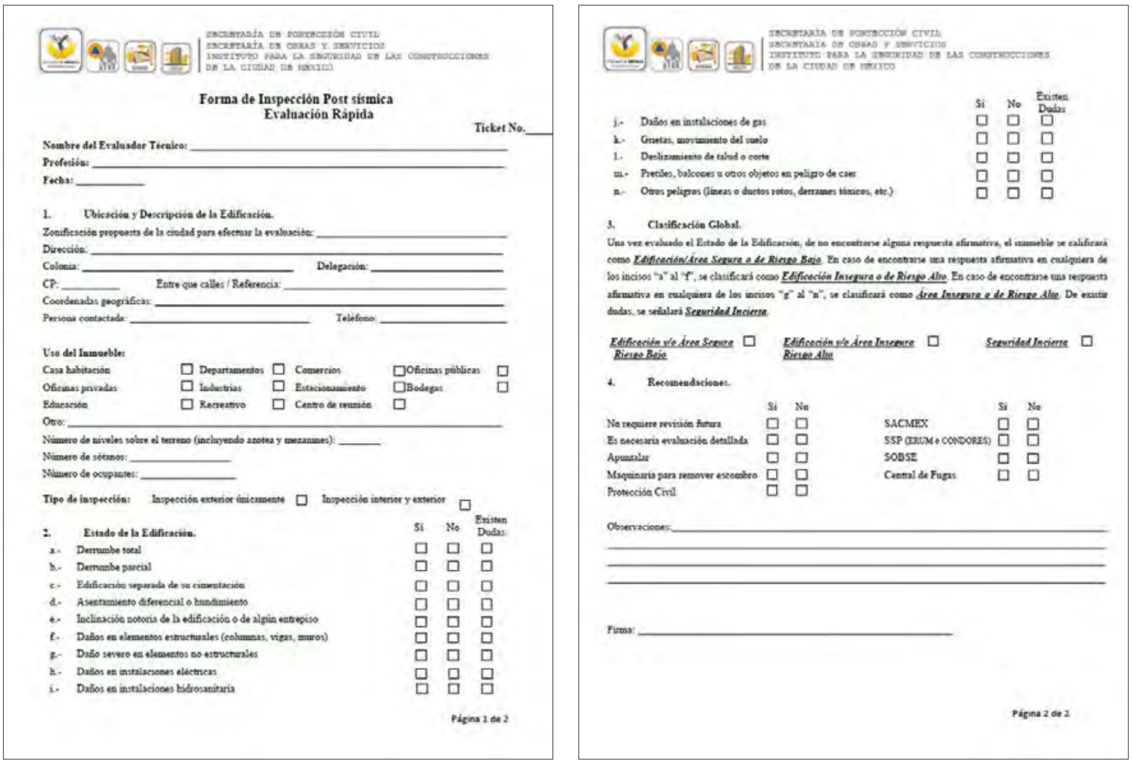


Figure 11.2 – Dynamic map of damage locations – based on the evaluations (source: www.plataforma.cdmx.gob.mxcomision)

The building classification was then made available online using an interactive map on the City of Mexico website (Figure 11.2). It should be noted that this map was produced by software originally designed to estimate the value of real-estate.



SECRETARÍA DE PROTECCIÓN CIVIL
SECRETARÍA DE OBRAS Y SERVICIOS
INSTITUTO PARA LA SEGURIDAD DE LAS CONSTRUCCIONES
DE LA CIUDAD DE MÉXICO

Forma de Inspección Post sísmica
Evaluación Rápida

Ticket No.____

Nombre del Evaluador Técnico: ____
Profesión: ____
Fecha: ____

1. Ubicación y Descripción de la Edificación.
Zonificación propuesta de la ciudad para efectuar la evaluación: ____
Dirección: ____
Colonia: ____ Delegación: ____
CP: ____ Entre que calles / Referencia: ____
Coordenadas geográficas: ____
Persona contactada: ____ Teléfono: ____

Uso del Inmueble:
Casa habitación ☐ Departamentos ☐ Comercios ☐ Oficinas públicas ☐
Oficinas privadas ☐ Industrias ☐ Estacionamiento ☐ Bodegas ☐
Educación ☐ Recreativo ☐ Centro de reunión ☐
Otro: ____
Número de niveles sobre el terreno (incluyendo azotea y mezanines): ____
Número de sótanos: ____
Número de ocupantes: ____

Tipo de inspección: Inspección exterior únicamente ☐ Inspección interior y exterior ☐

2. Estado de la Edificación.	Si	No	Existen Dudas
a.- Derrumbe total	☐	☐	☐
b.- Derrumbe parcial	☐	☐	☐
c.- Edificación separada de su cimentación	☐	☐	☐
d.- Asentamiento diferencial o hundimiento	☐	☐	☐
e.- Inclinación notoria de la edificación o de algún entrepiso	☐	☐	☐
f.- Daños en elementos estructurales (columnas, vigas, muros)	☐	☐	☐
g.- Daño severo en elementos no estructurales	☐	☐	☐
h.- Daños en instalaciones eléctricas	☐	☐	☐
i.- Daños en instalaciones hidrosanitaria	☐	☐	☐

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SECRETARÍA DE PROTECCIÓN CIVIL
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DE LA CIUDAD DE MÉXICO

	Si	No	Existen Dudas
j.- Daños en instalaciones de gas	☐	☐	☐
k.- Grietas, movimiento del suelo	☐	☐	☐
l.- Deslizamiento de talud o corte	☐	☐	☐
m.- Pretiles, balcones u otros objetos en peligro de caer	☐	☐	☐
n.- Otros peligros (líneas o ductos rotos, derrames tóxicos, etc.)	☐	☐	☐

3. Clasificación Global.
Una vez evaluado el Estado de la Edificación, de no encontrarse alguna respuesta afirmativa, el inmueble se calificará como ***Edificación/Área Segura o de Riesgo Bajo***. En caso de encontrarse una respuesta afirmativa en cualquiera de los incisos "a" al "f", se clasificará como ***Edificación Insegura o de Riesgo Alto***. En caso de encontrarse una respuesta afirmativa en cualquiera de los incisos "g" al "n", se clasificará como ***Área Insegura o de Riesgo Alto***. De existir dudas, se señalará ***Seguridad Incierta***.

Edificación y/o Área Segura Riesgo Bajo ☐ ***Edificación y/o Área Insegura Riesgo Alto*** ☐ ***Seguridad Incierta*** ☐

4. Recomendaciones.

	Si	No		Si	No
No requiere revisión futura	☐	☐	SACMEX	☐	☐
Es necesaria evaluación detallada	☐	☐	SSP (ERUM o CONDORES)	☐	☐
Apuntalar	☐	☐	SOBSE	☐	☐
Maquinaria para remover escombro	☐	☐	Central de Fugas	☐	☐
Protección Civil	☐	☐			

Observaciones: ____

Firma: ____

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Figure 11.3 – Evaluation sheet distributed by the Civil Protection of Mexico City

11.3 Main lessons

In Mexico, the absence of organized emergency diagnostic assessments for private buildings (offices and housing) led to a complex situation for residents. The absence of an identified interlocutor to which to turn made it difficult to obtain trustworthy diagnostics. The lack of a formal framework paved the way for the commercialisation of such assessments. This led to instances where the verdict of an assessment commissioned by a landlord contradicted that commissioned by the tenants; this situation was undoubtedly compounded by the absence of compulsory house insurance.

In order to avoid this kind of potentially dangerous and distressing situation it is recommended that these diagnostic assessments should be :

- Organized prior to events, within the framework of crisis management;
- Supported by a sufficient number of inspectors who are officially recognized and trained;
- Overseen by a single independent agency;
- Implemented using a single methodology;
- Free of charge and known to the population.

In view of the high number of inspections required following this particular event, the efficiency of the spontaneous arrangements and the strong participation of volunteers are interesting to note. In a difficult situation, faced with a limited number of inspectors, experienced personnel assumed the role of "Instructors in emergency diagnostics" with impressive results. Preparation for this kind of fast-track training could also form part of the on-going objectives of emergency assessment teams.

12 Geographic information systems

Geographic information systems (GIS) are designed to represent, compare, analyze and interpret georeferenced data. Over recent years, they have become powerful tools for all professionals using cartographic data. In this chapter, we highlight their use by the City of Mexico in the context of crisis management as well as their usefulness for an optimized rendition of the cartographic data acquired in the course of the AFPS mission.

12.1 Dynamic mapping

Emergency assessments provide a good example of the use of GIS in the context of crisis management following an earthquake. In the immediate wake of the September 19th 2017 earthquake, la Casa del Arquitecto effectively diverted real-estate sales software in order to monitor the emergency assessments in close to real-time.

The monitoring of diagnostic assessments was subsequently taken over by the CDMX (Ciudad de México) platform. On this open, online platform, a dynamic map (updated on a daily basis) allowed the situation of inspected buildings, plotted on an OSM background map (Open Street Map), to be monitored along with the conclusions of the assessments: collapsed building, building to be demolished, high-, medium- or low risk (red, yellow or green) building. It also featured the total number of buildings inspected.

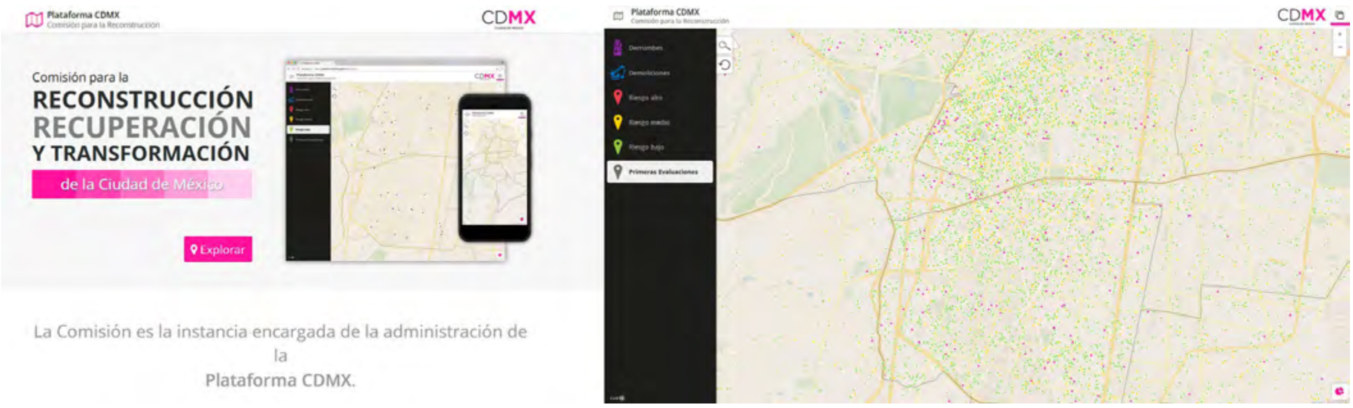

Figure 12-1 – Screenshot of https://plataforma.cdmx.gob.mx/ website

This open tool was extensively used during our mission in order to plot some of the site visits. Globally, the information available online was coherent with what was observed in the field, which demonstrates the quality of the GIS used in the earthquake context.

In France, an interface such as the interactive maps of the GeoRisques internet portal could – if this is not already planned – act as the basis for a cartographic system for crisis management in the event of a major earthquake, or indeed in the event of any other natural hazard.

12.2 Mapping of the mission

The post-earthquake mission, in a city as spread out as Mexico, involved a lot of travelling in order to record a maximum of observations and measurements. It was decided that the mission data should be stored in GIS format. The main categories of information contained in the GIS are:

- OSM base mapping of the city (roads, buildings, waterways, etc.);
- The tracking of a SPOT beacon carried by the mission set to one point every 10 minutes with additional points triggered manually;
- The precise position of H/V measurements and the information and results associated with each measurement point;
- The mission photographs (Today, mobile phones can take geolocalised photos. Location information can be retrieved in order to integrate the pictures as part of the GIS. In addition two GPS-fitted cameras were used during the mission).

The files obtained are in the “shapefile format”, which means that these goereferenced files can be read by all available GIS software packages. This mission by-product has the two-fold advantage of storing in one location all data acquired during the mission and of providing a digital rendition that can be used and consulted a posteriori. By providing direct information regarding the geographic locations of our observations, this type of data could eventually facilitate future post-seismic missions in Mexico City.

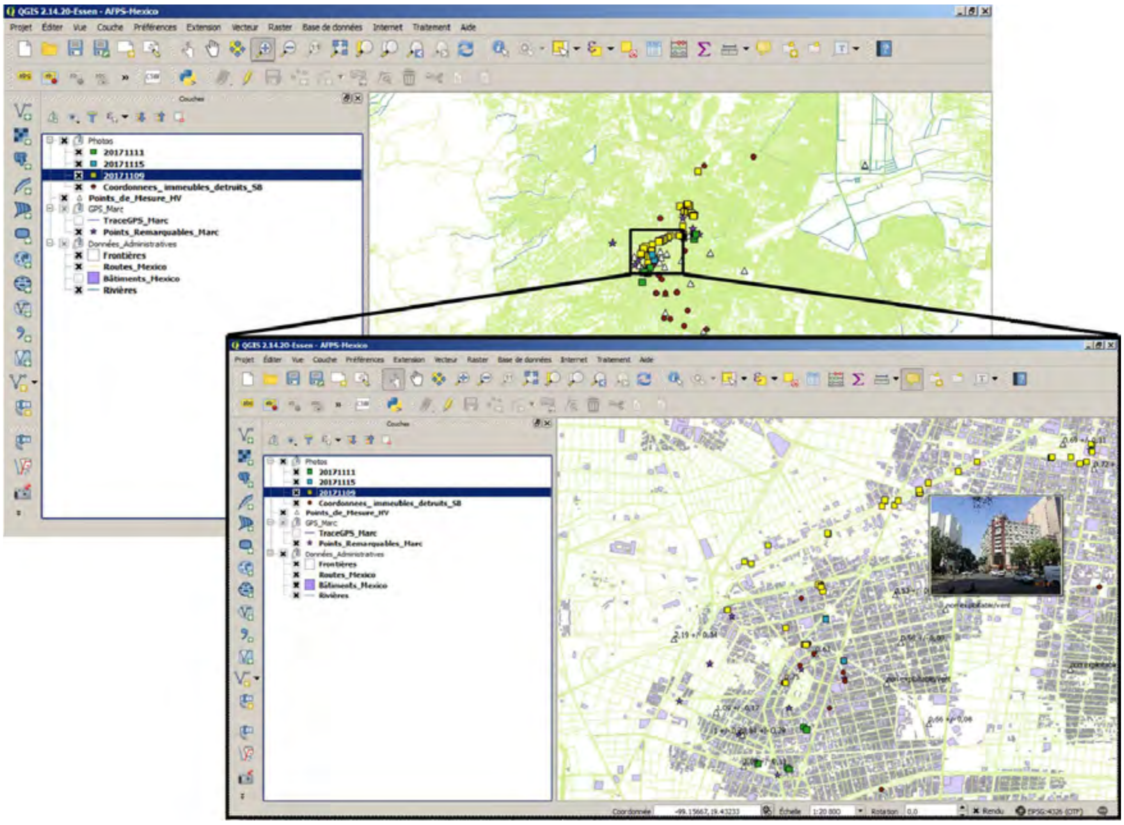

Figure 12-2 - Mission shapefile data displayed using the QGIS software. Top: an overall view of all the mission's movements across Mexico City. Bottom: detail showing the searchable aspects of the information layers, with display of photographs associated with the view point and the H/V measurement values.

12.3 Main lessons

The mission witnessed first-hand the significant contribution made by current cartographic tools, and notably GIS, in the context of crisis management. It was also able to appreciate the very open and accessible nature of the City of Mexico internet platform.

It recommends that such approaches, along with the necessary tools, be adopted and developed in France.

13 The earthquake as seen through the eyes of the media

13.1 Local press review

«Solidarity, as ever" was the headline of La Jornada the day after the September 19th 2017 earthquake.

On September 19th and 20th, the television and radio stations, as well as the print and internet media, were all reporting on the earthquake, emphasizing the damage and the victims. Simultaneously, the press was also relaying useful information concerning the rescue operations (location of shelters, government-run actions, rescue, volunteering, etc.).

On September 21st, the relentless efforts of the rescue teams and speculations regarding the extent of the damage shared the newspaper headlines. Ten days or so after the event, the news started to deflate somewhat and other news began to occupy the headlines. Thus, on October 2nd, a mere thirteen days after the earthquake, the Catalonia referendum was the front-page news and the ongoing reconstruction works had been relegated to secondary information.


La Jornada

COMO SIEMPRE LA SOLIDARIDAD

Al menos 224 muertos por el sismo de 7.1 grados

En la capital del país se colapsaron 44 inmuebles

"Es una nueva prueba y muy dolorosa": Peña Nieto


La Jornada

EN EL REFERENDO CATALÁN, 90% POR LA INDEPENDENCIA

Puigdemont: nos ganamos el derecho a ser un Estado soberano

Rajoy: hicimos lo que teníamos que hacer para defender la unión de España

■ Sí habrá recursos del Fonden para capitalinos: Mancera

Destacan la labor de mujeres en el rescate de atrapados

Estiman que aún hay 8 cuerpos en Álvaro Obregón 286

■ "No tenemos la fuerza de un hombre, pero sí muchas capacidades"

■ Cenapred: miles de inmuebles dañados requieren revisión meticulosa

■ Revoca la SEP autorizaciones al Rébsamen para servicios educativos

Figure 13.1 - Headlines of the La Jornada newspaper, on D+1 (left) and D+13 (right)

Mention must also be made of the specific role played by social media networks in the dissemination of information. The rescue organization, for one, benefitted greatly from the fast transmission of huge amounts of information on the social networks. But sensationalists also had a field day. Unverified information and rumors spread like wild fire. Whether for better or worse, is difficult to decide.

13.2 Coverage of the event by French correspondents

When one enters the query «Earthquake Mexico 2017» in a search engine, the first results that appear correspond to the internet sites of media organizations (television, radio, written press, etc.). It is only when one has reached the bottom of the second results page that the IPGP website appears (Institut de Physique du Globe de Paris) with some qualitative scientific information on the earthquake. The vast majority of the information directly accessible by the public comes therefore from the media, either via the conventional channels (TV, radio, press) or via the internet. In order to understand how, under degraded conditions, this information was collected, transcribed and broadcast in France, we met with the local director of the AFP (Agence France Presse) and with a free-lance journalist based in Mexico City.

- Safety and operationality under degraded conditions

The AFP offices in Mexico are located in the Roma district, one of the most impacted by the earthquake. The two storey building was strongly rocked during the event but withstood it quite well. Following the first tremors, the personnel rapidly exited the premises and gathered in a nearby square, the designated assembly location in the evacuation procedures put in place by the agency.

Immediately afterward, the necessity to remain operational and in a capacity to cover the events and to send information came to the fore. With this objective in mind, the AFP could rely on a contingency plan, which included mobile logistical resources (portable satellite systems, power generators, etc.) and several pre-identified potential safe locations for establishing crisis headquarters.

- **The collection of information**

The collecting of information is a multifaceted process. One source is on-site observations. In this respect, the first difficulty lies in the complete disorganization of the town, with blocked access roads and the absence of public transport; to overcome this, motorcycle delivery drivers were hired to reach earthquake-struck locations. The second difficulty lies in gathering the information itself while emergency, panic and distress prevail all around and the presence of observers could potentially heighten tensions.

Regarding the more technical information concerning earthquake characteristics and impacts, the main source is the local media. Any statements from the Civil Protection officials are of particular interest as they convey represent official channels of communication.

- **Transmission and dissemination of information**

In the first moments following the earthquake, when only the mobile network remained operational, the transmission of information towards France, in the form of video images for instance, was achieved using the What's App application. The journalistic content is thus provided to the French media who then select which of the subjects they will run, in line with their editorial policy.

Trying to avoid sensationalism but nonetheless striving to reflect the reality of a human drama where 300 people lost their lives, the first images of the September 19th 2017 earthquake to appear on French screens showed the rubble and the rescue teams searching for survivors. French media coverage of the event was in itself relatively short-lived, lasting only two or three days.

- **Perception from France**

Even though information concerning the earthquake was only broadcast over a period of a few days, without any excessive coverage, the images focused on the destruction in the zone around the forty or so collapsed buildings. This produced the impression of a city where the level of destruction was massive. Within the mission, we were struck by the difference between what we expected to encounter in-situ and the actual damage observed once there. On the scale of a city such as Mexico, the amount of destruction, although tragic, remained limited. Incidentally, in order to show that most of Mexico City was still standing, the AFP flew a drone equipped with a video camera over the city one month after the earthquake. These images only attracted the interest of one French media organization.

Figure 13.2 – Images broadcast on BFM TV (left) and published in Le Monde, September 20th 2017 issue, p. 6 (right)

13.3 Main lessons

During our mission, we were able to observe how prompt and efficient the media can be in a crisis situation, as is often the case. We also noted how quickly information wanes in importance: thirteen days after the event, the earthquake was no longer front-page news in Mexico.

We were also able to verify that, as often during a crisis, the media were the cause of a marked "magnifying effect". As they tend to focus more on the tragic and the spectacular, the perception of the events from afar is often very distorted.

As a principal lesson, we recommend that the exchanges we had with journalists on the ground should be continued. In fact, it is important for a scientific team to understand the difficulties encountered by the media in times of crisis. In return, journalists are open to contributions from scientists that might lend more depth to their coverage.

14 Architecture

14.1 Contemporary Mexican architecture

Contemporary Mexican architecture is recognized and admired worldwide. Its most distinguished representative is Luis Barragán (1902-1988). He was awarded the 1980 Pritzker Prize (the most prestigious international award in the field of architecture) and is regarded as the equivalent of Le Corbusier. Barragán's house and studio have been listed as a World Heritage site.

In France in 2003, the Electra Foundation hosted an exhibition on Mexican architecture entitled «Les Bâtisseurs de lumière» ("Builders of Light"). In the catalogue we learn that "Today Mexico is home to 140 architectural schools, with 18 in the Valley of Mexico alone, and 60,000 students which is more than in the entire United-States!"

The starting point of the exhibition was to explore the "post-Barragán" landscape, looking at three generations of architects influenced to various degrees by this founding father of Mexican modernism. The exhibition curator identified three movements: «Expressionism» which makes use of the plasticity of concrete, the «Metaphysics of color» which takes its inspiration from the works of Barragán and the colonial heritage, and finally «Internationalism» which favors light structures of steel and glass.

It is with these references in mind that we set about our mission in Mexico. We were particularly struck by the beauty of the vividly colored building where we met with the Civil Protection representatives of Puebla: The William O. Jenkins Convention Center.

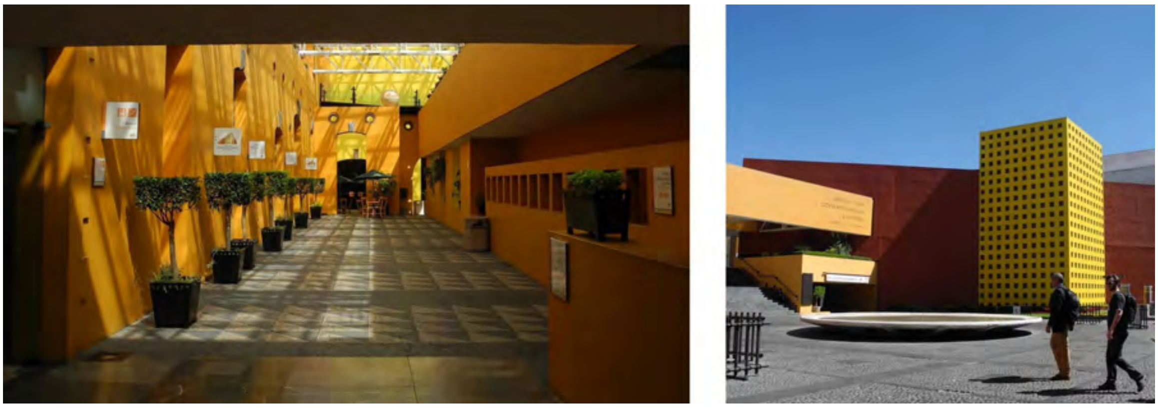

Figure 14.1 – William O. Jenkins Convention Center in Puebla

Opened in1998 and only completed in 2009, this 33,000 m2 complex, designed by the architect Javier Sordo Madaleno, amalgamates former textile factories bearing poetic names such as La Guia, La Esperanza, La Mascota et La Pastora (The Guide, Hope, The Mascot and The Shepherdess): it combines historic buildings and very contemporary structures. The Center presentation leaflet mentions that, through this project, buildings of historical and artistic value were saved thanks to the perfect balance struck between cultural and the commercial aspects and between modern and the historic styles.

To this description, we might add that the complex, though composed of very heterogeneous structures, is endowed with remarkable anti-seismic qualities. Not only did the structures behave quite well during the earthquake and did not sustain any damage, but the center itself was fully operational when we visited it, as was the «Centro de Analisis» of the Civil Protection which is based here.

Based on this example, it has to be said that anti-earthquake engineering and inspired architecture sometime come together surprisingly well, in Mexico at least[6].

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[6] Similar remarks were made in the context of other AFPS missions. For instance in Colombia we noted that the City Hall in Armenia had been severely damaged and rendered unusable by the January 25th 1999 earthquake, and that its functions had been transferred to Quindio Museum, a magnificent building designed by Rogelio Salmona, the most celebrated Colombian architect who had worked under Le Corbusier in France.

Likewise, in India, where the Gandhi Labor Institute in Ahmedabad emerged unscathed after the January 21st 2001 Bhuj earthquake. This building was designed by Balkrishna Doshi, an Indian architect who had also worked with Le Corbusier in France. Later during the same mission, as he showed us through his undamaged offices after the earthquake, the architect Shah Sneha who was working with Mario Botta on a major project for the Tata Group, explained that the fifty buildings which had collapsed in Ahmedabad were the product of developer-led architecture rather than architect-led architecture. The 2017 mission convinces us further of the anti-seismic benefits of this architect-led architecture.

14.2 Anti-seismic esthetics

When one looks at the evolution of contemporary architecture in Mexico City over the last fifty years, one cannot help but be struck by the gradual emergence of an esthetic whose inspiration is clearly anti-seismic.

This is evident along the Paseo de la Reforma, Mexico's 14.7 km long avenue. Created in the 19th Century on the orders of Maximilian 1st, this avenue retraces the whole history of architecture from the end of the 19th Century to the beginning of the 21st; virtually all of the styles from this period are represented.

The «Art deco»-style was succeeded by the «international style», which became prominent. Buildings typical of this style resemble opaque, perfectly shaped boxes, often with smooth curtain walls, generally quite expressionless. In reaction against the impersonal aspect of the «international style», the "postmodern" wave of the 1990s is more complex and quirky.

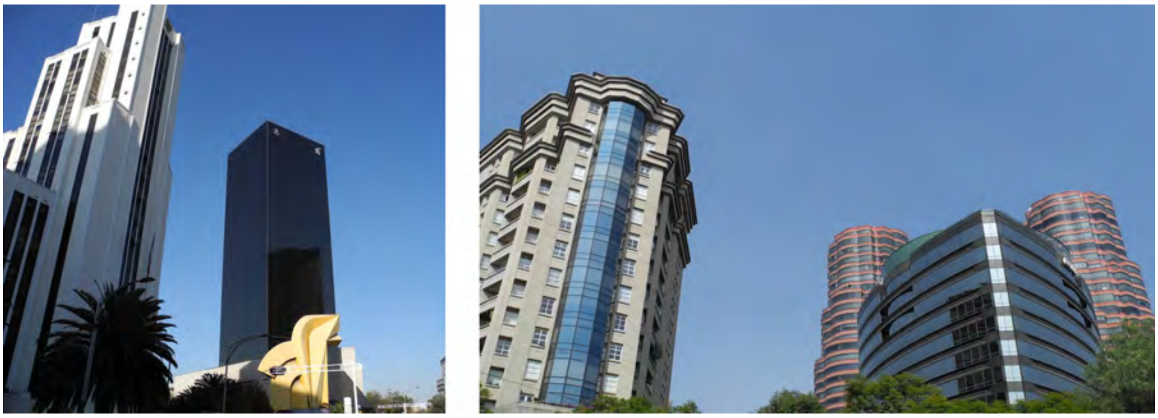

Figure 14.2 – Evolution of architectural styles in Mexico City

In Mexico City, one building is emblematic of this trend: the CFE building (Comisión Federal de Electricidad), which is often use to illustrate the concept of «triumphant postmodernism».

But it could just as well be labelled «the triumph of anti-seismic design». In Mexico, which is a federal state, there are no national anti-seismic regulations, each state being responsible for implementing its own rules. However, a common design manual exists, the «Manual de diseño de obras civiles - diseño por sismo» published by the CFE.

And it is a credit to the authors of this manual that the CFE building, which is neither particularly simple nor regular, but whose red skeleton is a powerful statement, behaved perfectly during the recent earthquake.

Figure 14.3 – The CFE building, la Comisión Federal de Electricidad

Following the 1985 earthquake, many buildings were retro-fitted with very visible and very expressive steel elements which were added to their façades. Originally probably not designed to last, these emergency reinforcement measures became permanent and eventually endowed the buildings with a strong sense of stability and strength.

This effect can be observed on the IFAL building (French Institute of Latin America) where the exposed cross bracing on all sides creates a rather reassuring feeling.

Figure 14.4 – Seismic retro-fitting of buildings after 1985

In new buildings, we are now seeing visible bracing elements on the façades. Initially such elements tended to be barely visible behind glass cladding, their presence hinted at but not flaunted.

Figure 14.5 – Transparency and bracing

Over time, they have become more obvious design features and in recently-designed buildings they constitute a veritable esthetic statement: «I'm beautiful but tough enough to stand up to an earthquake!»

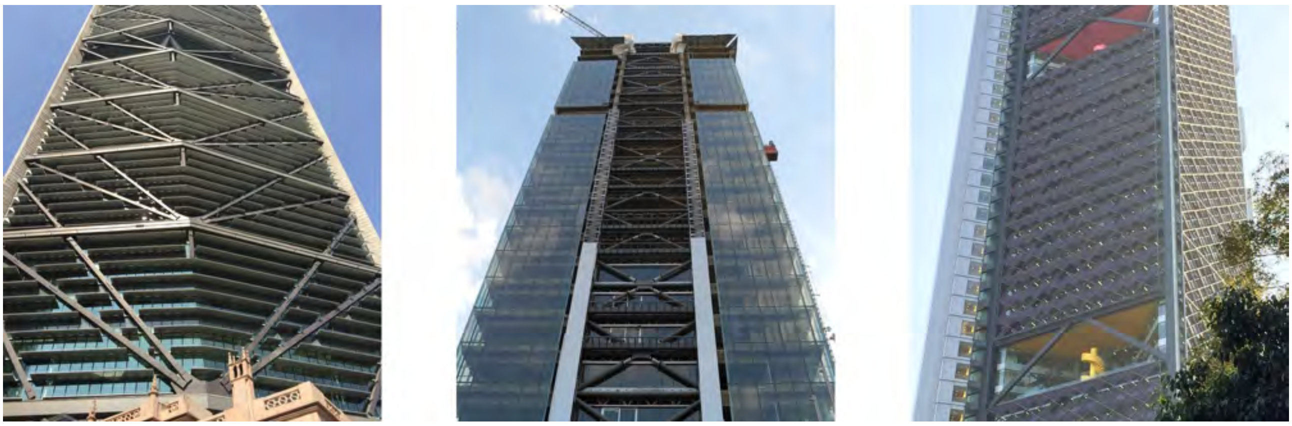

Figure 14.6 – Visually affirmed bracing on recent buildings

In this regard, it is worth considering la Torre Reforma. Completed in 2015, this 57 story tower was the highest building in Mexico[7] for a year . It was designed and built by the architect Benjamin Romano and the engineering firm Arup, The presentation leaflet boasts that this is one of very few buildings in Latin America to be built without columns and that it has a "design and structure combining the best of national talent with international technology".

In this leaflet, we also learn that the Arup engineering firm carried out a state-of-the-art seismic analysis, taking into account a 2,500 year return period which far exceeds the period recommended by the current directives. In 2017, the building behaved very well and was in perfect working order when we visited it.

[7] *In May 2016, it lost its title to the Torre KOI, a 279 m tower erected in a suburb of Monterrey.*

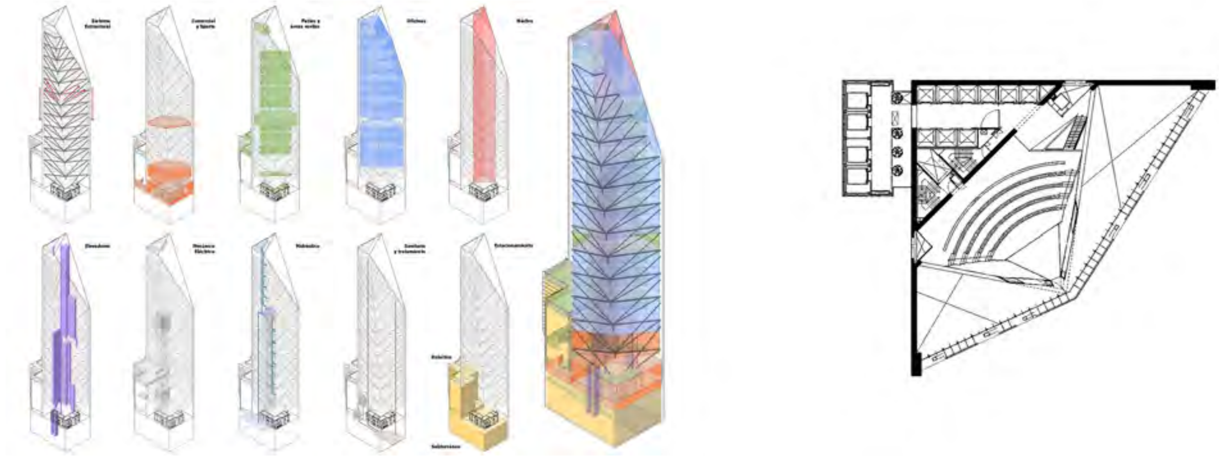

Figure 14.7 – La Torre Reforma: schematic principle and layout of level 24 (© torrereforma.com)

Its structure is quite specific. It is based on two main concrete shear walls, arranged perpendicularly, and floors suspended using tie rods on the façade. The concrete shear walls necessitated the design of very special foundations: these foundations, constructed by Cimesa (the Mexican subsidiary of Soletanche Bachy) are composed of very thick (1.20 m) diaphragm walls which were driven down to a depth of 60 m.

Figure 14.8 – La Torre Reforma: pictures of the construction site (© curbed.com)

Since a square-cornered shape is sensitive to torsion, the corresponding stress is transferred by the façade tie rods and at ground level, with all forces converging on a spectacular assemblage. To boost the dramatic effect of these concurrent forces, a glass floor in the entrance hall allows this nodal point to be admired. The theatricality of the design is made complete by the glass ceiling of the underground restaurant, which allows the structure to be admired from all angles. As we look in awe, we can only wish that we had been present on the day of the earthquake to witness the mechanism in operation.

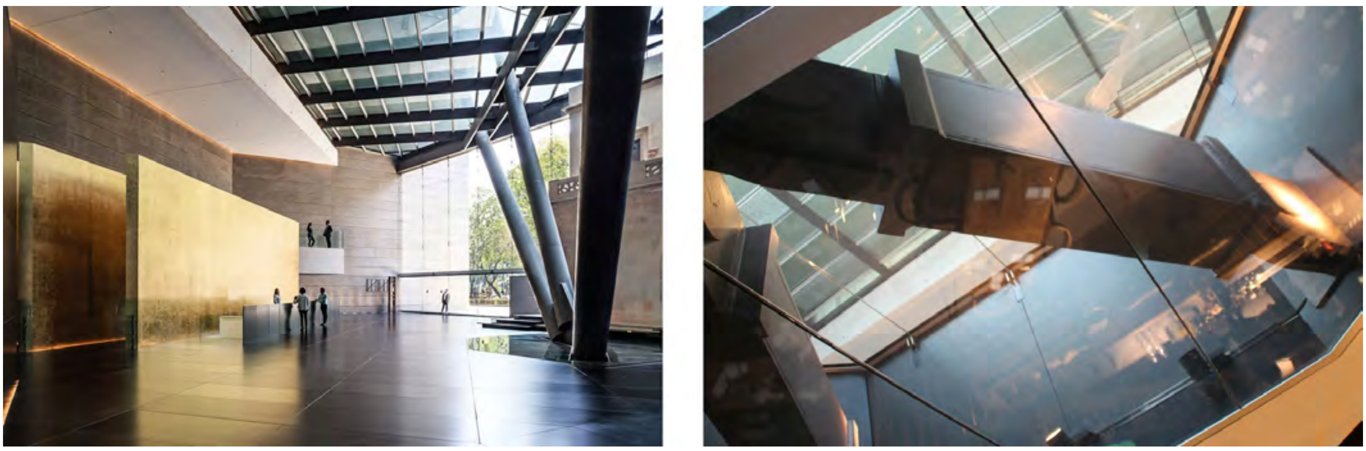

Figure 14.9 – View of La Torre Reforma from the hall (© torrereforma.com), Glass ceiling of the underground restaurant

14.3 The responsibility of the architect

In the context of our mission, we were able to observe that, apart from a few exceptions, recent buildings (built after 1985) behaved adequately. Unfortunately one of these exceptions was a school whose tragic collapse generated a lot of media attention.

The facts are as follows: At 11:00 on September 19th the “simulacro” (post-seismic drill) took place in the Enrique Rebsamen School, as it had every year on the same date since 1985. The drill proceeded normally, but at 13:34, a real earthquake struck and part of the school building completely collapsed before the eyes of horrified parents. As often nowadays in our hyper-connected societies, people started filming using their smartphones and images rapidly found their way onto the social networks. Many people spontaneously rushed to take part in the rescue operations which would go on for several days under terrible conditions, as attested to by the images. Tragically, this disaster would claim the lives of 19 children and 7 adults.

Figure 14.10 – Rescue operations at the Enrique Rebsamen school (©AFP / Mario Vazquez)

Clearly, it is not our place to pronounce judgment on this tragedy or to assign responsibility. A judicial process, which will be long and painful, is currently under way and will consider all associated expert assessments. However, one point struck us particularly: In the press, the school management was accused of having raised the height of the building and certain individuals were named, such as those of the engineers who are believed to have sanctioned the works by issuing favorable opinions («dictamen») in 2010 and 2014. However, the names of the architects who supposedly oversaw the construction and extension works were never mentioned (in France, if an airport terminal collapsed at Roissy, or if a balcony fell somewhere in Issy-les-Moulineaux, the press would not hesitate to publish the names of the architects involved).

Figure 14.11 – The Enrique Rebsamen school building before and after the event (internet images)

Evidently errors were made, there were short-fallings and omissions on the part of the constructors and, considering the extent of the collapse, the building obviously suffered crucially from a lack of stabilizing elements to combat horizontal stress. Beyond the issue of legal responsibility, there are lessons to be learnt from this tragedy for the benefit of all architects. Etymologically, the architect is the arkhós-tektôn, the head of the builders. Therefore, ultimate responsibility lies with the architect to design projects that can withstand horizontal stress and to anticipate the provision of the stabilizing elements required to prevent his/her buildings from collapsing like a house of cards.

14.4 Architectural training in Mexico

Ultimately, the issue of the responsibility of the architect raises the question of architect training. We had the opportunity to discuss this topic with a young French conservation architect who had finished his training at the «Facultad de Arquitectura» of the l'UNAM in Mexico City. He told us that the UNAM does not offer any specific courses in anti-seismic design but that the issue is omnipresent throughout the curriculum.

In fact, earthquake engineering is fully integrated within the teaching, in particular as part of the compulsory «sistemas estructurales» (structural systems) modules that are rolled out over 6 semesters. As early as the first semester, buildings are treated as «sistemas de transmision para cargas gravitacionales» (gravitational load transmission systems) and as «sistemas de transmision para fuerzas horizontales» (horizontal stress transmission systems). And the 3rd semester reading list includes works such as «Construcciones antisismicas y resistentes al viento» and «Diseno de estructuras resistens a sismos».

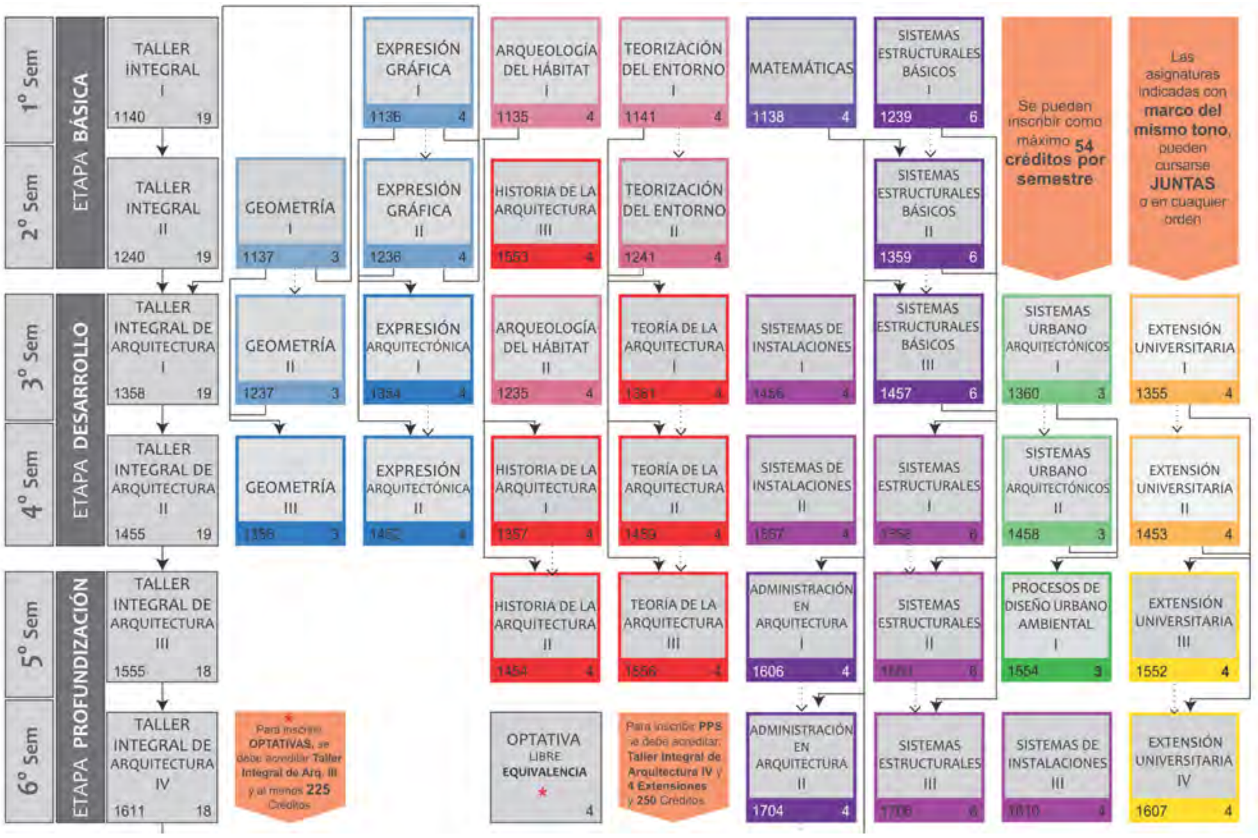

Figure 14.12 – Curriculum for the first 6 semesters at the «Facultad de Arquitectura» of the UNAM

The «taller de arquitectura» (architecture workshop), which forms part of the 3rd semester construction course, covers topics such as the seismicity of Mexico City, the geotechnical characteristics of the site, wave amplifications and the dynamic properties of soli dynamic.

By comparison, in France the issue of earthquake engineering in architecture is taught as a specialty course. It is the subject of the "Earthquake-resistant Constructions» DPEA (Post-master Research Diploma in Architecture) in Marseilles and of the «Architecture and Major Risks» DSA (Specialized Post-master Degree) in Paris. In a country where an estimated 21,000 communes are concerned by seismic risks, the idea of restricting the anti-seismic training to a few "specialists" leaves us somewhat skeptical and a Mexican-type approach should undoubtedly be envisaged for the training of French architects.

14.5 Main lessons

In this chapter we have seen that in Mexico the consideration of seismic risks has not implemented at the expense of architectural quality and diversity. On the contrary, we found that seismic risk could be the source of significant architectural creativity. Hence, contemporary Mexican architecture, already well known and publicized in France, should continue to receive particular attention.

We also noted that in the architectural instruction provided in Mexico, awareness of the seismic risk was an integral part of the basic training of every architect and was in no way a specialty subject. We can only advise that the same approach be developed in France.

15 Historic buildings

15.1 The issue of built heritage and the threat posed by earthquakes

For the French seismic engineering community the issue of the threat of earthquakes to heritage buildings is a recent development. It emerged mainly as a consequence of the last seismic events in Italy. In the framework of this mission, we were particularly struck by the similarities that exist between the approach followed in Mexico and that implemented in Italy.

In Puebla, the official in charge of the Historical Center and of the city's Cultural Heritage, Sergio A. De La Luz Vergara Berdejo, made a very interesting presentation on the subject and provided us with a very substantial document entitled «Manual de procedimientos del patrimonio monumental de Puebla para efectos de sismo». This 220-page document constitutes a manual of procedures (as indicated by the title). In the context of the present report, necessarily succinct by nature, it was not really possible to comment on it in detail [8], however, the document is looked at in relation to similar Italian equivalents. These manuals, both Italian and Mexican, would deserve to be translated into French.

Figure 15.1 – Cover of the Puebla Manual

In Mexico City, the National Coordinator for Historical Monuments, the architect ArturoBalandrano Campos, and his assistant, the architect Manuel Villaruel, outlined to us the functioning of the INAH administrative entity (Instituto Nacional de Antropología e Historia) which is in charge of Mexico's heritage. They also provided us with detailed information regarding the PREVINAH program (Programa Nacional de Prevención de Desastres en Materia de Patrimonio Cultural).

The INAH prerogatives are both clear and simple. They concern:

- The totality of the paleontological, archaeological and anthropological heritage, which is regarded as "national heritage" and consequently cannot be the property of anyone (in short, this covers all heritage pre-dating the Spanish colonization);
- All buildings constructed between the 16th and 19th Centuries, regarded as "historical" (both public- and privately-owned buildings are placed under INAH supervision).

In total, 17,000 buildings fall under the auspices of this institution. During the 2017 earthquake, 1,821 were negatively affected: 20% suffered collapse, 60% suffered non-structural damage, and 20% suffered simple cracks. The institute therefore has its work cut out in terms of post-seismic interventions, but it is also involved in the development of active prevention policies. The preventive conservation manuals that it publishes deserve to be more widely known. They pay particular attention to the seismic risk and, incidentally, we note that the INAH logo is a stylized representation of the logographic glyph meaning «terremoto» (earthquake).

Figure 15.2 – Extract from the Codex Telleriano-Remensis *Logo of the INAH*

[8] This manual is available on line at http://consejocentrohistoricopuebla.com/ and will be included as part of the mission appendices.

15.2 Puebla

The City of Puebla, whose official name is Heroica Puebla de Zaragoza [9], is also known as Puebla de los Ángeles. In 1987, its historical center was listed as a UNESCO world heritage site on account of its well-preserved urban layout and for the quality of its buildings.

On June 15th 1999, the historical center was hit by the Mw 7 earthquake (MMI VIII intensity) which caused 25 deaths and more than 200 injuries in the Puebla region. Numerous historic buildings were severely damaged with significant partial collapses.

Following this earthquake, major repair and preventive retro-fitting works were initiated and the mission was glad to observe their beneficial impact. During our visit on November 13th 2017, we could see for ourselves that most buildings were intact. Admittedly, some buildings were being supported by struts and reinforcement was visible on church spires, but no building collapses, even partial, had occurred.

Figure 15.3 – Views of Puebla city center

Figure 15.4 – Puebla, view of a number of churches exhibiting minor damage

Figure 15.5 –Puebla Cathedral, strengthened following the 1999 earthquake, is in perfect condition

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[9] *The city is dear to Mexican hearts since the army of General Ignacio Zaragoza defeated French troops there on May 5th 1862. Since then, «El Cinco de Mayo» is celebrated in Mexico. In 2012, a 10 peso coin bearing the image of General Ignacio Zaragoza was issued to commemorate the 150th anniversary of the victory over the French.*

15.3 Mexico

In Mexico we saw that some monuments had suffered significant damage and that clearing and shoring work was under way. At Nuestra Senora de los Angeles half of the dome had collapsed into the church, and in Nuestra Senora de Loretto struts were being put in place. Nonetheless, the vast majority of historic buildings were open to the public.

Figure 15.6 – Mexico City: Collapsed dome of Nuestra Senora de los Angeles, ongoing shoring work in Nuestra Senora de Loretto

However, on closer examination of the monuments, numerous incidences of tilting in all directions, sometimes quite astonishing in their degree, became apparent. This could be regarded as almost "normal" in a place like Mexico City where the soil becomes gradually compacted and not necessarily in a homogeneous fashion, and where the verticality of buildings can vary greatly; often the degree of tilting is inversely proportional the date of construction.

Seismic dynamics may sometimes amplify such phenomena, but it is fundamentally the statics of a structure, i.e. infinitely slow-varying forces, that explains the "tilted" aspect of many buildings. A beautiful example of this mobile aspect of Mexico City can be found in the Cathedral where a pendulum continuously indicates the variation of the nave's displacement, acting almost as a permanent seismometer. In Mexico, people are accustomed to the movements that are part of the life of a building.

Figure 15.7 – Mexico City: various examples of tilting, the Cathedral and its pendulum

15.4 Main lessons

In this chapter we have seen that in Mexico, as in Italy, the recognition of seismic risks to historical buildings has been treated as a specific issue with specific approaches.

We can recommend that this issue become more developed in France and that we build on the wealth of experience accumulated by countries more prone to earthquakes.

We believe that this issue deserves to be at the center of a specially dedicated, in-depth mission. Considering the brevity of our mission and the vast scope of the issues treated, this report can only be regarded as a first step.

We also note that our interlocutors expressed a strong interest in the idea of organizing an international meeting of experts on this topic. From a diplomatic point of view, France, which hosts the UNESCO[10] headquarters in Paris, would be particularly suited for the hosting of such an event.

[10] *One of Unesco's missions is to "protect our heritage and encourage creativity" and its general secretary is a former French Minister for Culture.*

16 French buildings in Mexico City

In the framework of our mission, we were asked to evaluate the situation of French buildings in Mexico City. Following the 1985 earthquake, the French Ministry of Foreign Affairs invested heavily in strengthening its properties there and it seemed an ideal occasion to reassess the state of these buildings.

16.1 Technical assessments performed

In relation to French diplomatic buildings and cultural institutions in Mexico, we were in a position to visit and meet officials in charge of the Embassy and the General Consulate, the French Institute of Latin America (IFAL) and the Casa de Francia.

The Embassy and the general consulate are housed in a building constructed between 1992 and 1996 to a design by the French architect Bernard Kohn. It is a rather complex structure with a surface area of 16,850 m2 and comprising 13 floors including underground car parks with a 110 car capacity. From a structural point of view, the building behaved quite well. The only instances of damage we observed were a cracked partition wall in a meeting room on an upper floor, a few cracks at the junction between the concrete frame and a number of brick infills, and some dislodged cladding elements on the façades. All in all this was quite minor, "normal" damage considering the strength of the earthquake.

Figure 16.1 – The French Embassy in Mexico City

The IFAL institute was founded in 1944 by the then "Free France" government of General De Gaulle. The original plans were drawn up in the period between 1954 and 1963 and the actual construction was carried out in 1973, with additions in 1977- 1978 before the 1985 earthquake. In 2000, a major program of seismic retro-fitting was conducted. On the plans that we were able to examine, this is termed «rigidizacion edificio» (rigidification of the building). We were impressed by the quality of the technical dossier compiled by the Mexican engineer Garcia Jarque[11] : 3D modeling, calculation notes, detailed building plans including underpinning.

We were able to observe that this rigidification functioned adequately in 2017 as the building displayed only minor cracks, again at the junction between the concrete frame and the brick infill. In this case, the advantage of rigidification is two-fold: on the one hand it strengthens the structure's stability against horizontal stress (the stability is likely to have been quite weak beforehand. Even though the building survived the 1985 earthquake, it must be regarded as a vulnerable structure), and, on the other hand, it significantly modifies the natural period of the building and, hence, its position on the dimensioning spectrum, with a very favorable impact in terms of stress in this case (of course this depends on the nature of the soil).

Figure 16.2 – The French Institute of Latin America (IFAL) in Mexico City

[11] In passing it is worth highlighting the fact that a building's technical archives can be very valuable in a post-seismic situation or for later interventions, and it would be judicious to have them digitized and to have several copies stored in different locations.

The Casa de Francia is the former French Embassy. It is one of the last 19th century buildings still standing in this sector and is surrounded on all sides by towering high-rises. In 1998, it was transformed into a cultural center by the French architect Bernard Desmoulin. This subtle makeover resulted in a very elegant building which is appreciated as the representation of France in Mexico City. In a 2015 interview, Bernard Desmoulin deplored the fact that “beauty had vanished from the architects’ discourse. It has been banished since the 17th Century, and it already looks like it won’t be back in the 21st”. Obviously this is not the case in Mexico with La Casa de Francia. But this elegance has not been achieved by ignoring the seismic risk. Indeed, the building was in excellent condition when we visited it, apart from minor traces of scraping on a flagstone at the entrance which was the result of a collision between the building and the external stairs.

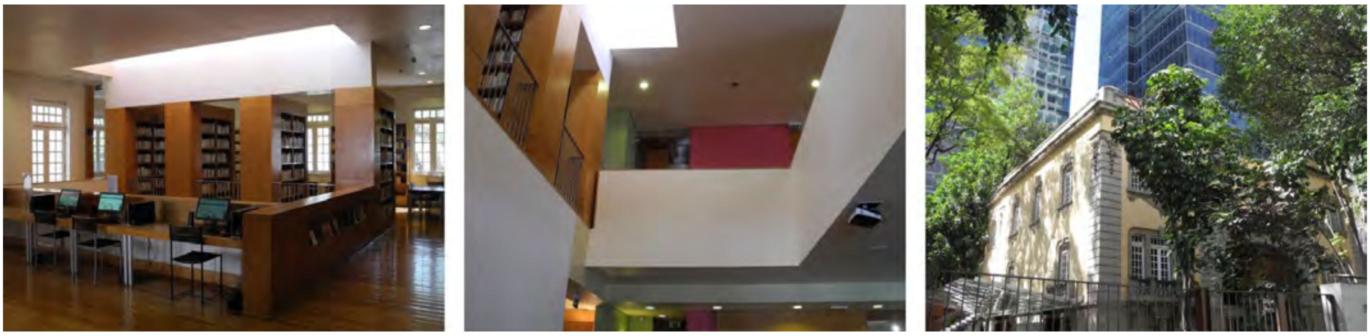

Figure 16.3 – La Casa de Francia in Mexico City

16.2 The unfolding of the crisis

We had very interesting exchanges with the personnel in charge of these buildings regarding the sequence of events on the day of the earthquake. Based on these, we would like to highlight a few points:

- The alarm was triggered only a few seconds after the earthquake occurred (which is to be expected as earthquake was much closer to Mexico City than its 1985 counterpart).
- During the earthquake, people gathered, as planned, in the designated safer areas of the building (generally close to elevator shafts).
- When the earthquake was over, the buildings were evacuated and everybody gathered at the assembly points
- It was only possible to return to the buildings after the official “dictamen” had been issued by an engineer registered on the official list of engineers: this took several days.

Overall, the outcome was positive: there were no casualties and French services were open to the public at the time of our mission (which was not the case for all countries represented in Mexico City). However, there are a number of comments that must be made regarding the sequence of events:

- To rely for safety on forecasting and alarm systems can be delusive
- The order to evacuate or remain in a building deserves to be considered on a case-by-case basis (While it is safer to exit a building threatening to collapse, it can sometimes prove more dangerous to leave a safe building and find oneself in an even more hazardous environment because of the surrounding buildings).
- In any case, defining the safest zones in a building is good practice. It would be judicious to check the anchoring of elements susceptible to fall in these zones.
- The procedure for returning to the premises should be improved timewise and it would be desirable if emergency post-seismic diagnostics could be conducted in-house.

16.3 Main lessons

We have seen that following the 1985 earthquake, France had initiated a significant program of retro-fitting and reconstruction work to its buildings. On location, we were able to observe that not only was this program effective but it also produced some high quality architecture. We recommend that similar programs be implemented in all earthquake-prone countries in the world where France is represented.

On a technical level, we believe that it would be judicious that the following measures are taken:

- Building technical managers should be trained and accredited to conduct emergency post-seismic diagnostics;
- Building technical documentation should be digitized and stored in several locations ;
- For each building, pre-diagnostics should be carried out (for a building already identified) so that a summary document, which can be easily used in a post-seismic situation, can be prepared in advance;
- Fire safety plans should be supplemented with a schema allowing a rapid on-site distinction to be made between structural elements and non-weight bearing, infill elements.

17 Thoughts on urbanization

«Towns should be built in the countryside; the air is so much purer there.» Alphonse Allais (1855 -1905)

In France, when one evokes Mexico City and seismic risks, the above proposal by the French humorist Alphonse Allais often comes to mind. Indeed, why on earth was one of the largest agglomerations in the world established and allowed to expand in such an earthquake-prone area!

To answer this question, it is necessary to go back to the distant past. When considering seismic risk, seismologists are accustomed to dealing with geological time-scales, spanning tens of thousands or even millions of years; the situation in what is now Mexico City has certainly existed for quite some time and will no doubt continue into the future. In this chapter we will consider a much shorter timescale, that of human time.

The first humans are believed to have arrived in Mexico approximately 20,000 years ago, having crossed the Bering Strait. The first known civilization to develop in the region was that of the Olmecs, dating from 1500 BCE, during which clay pyramids were built. This civilization declined and disappeared around 900 BCE.

Subsequently, the Maya civilization developed and culminated during the so-called "classical" period between 200 and 900 CE. Its major achievement was the theocratic city of Teotihuacán, located ca. 40 km north-east of Mexico City. Its name means "the place where the gods were born", and it is estimated that it was once home to 200,000 inhabitants. We know that the Mayas experienced earthquakes: they recorded them in dedicated chronicles and created a specific glyph to represent the phenomenon. Another, more indirect proof lies in their architecture. Some archaeologists have compared the Pyramid of the Sun with the Great pyramid of Giza and have found that, even though they have similar base dimensions (225 m), the Maya construction is only half the height of the Egyptian example (65 m as opposed to144 m). This difference could be explained by anti-seismic stability considerations.

Figure 17.1 – Model of the city of Teotihuacán

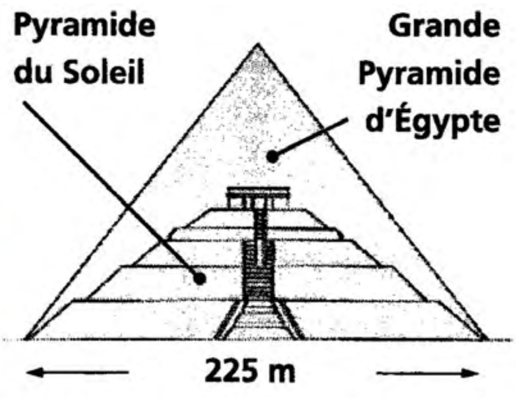

Figure 17.2 – Comparison of the heights of the pyramids

For reasons that are still unclear today, the city of Teotihuacán was abandoned sometime in the 6th Century. Towards the middle of the 13th Century, a pre-Columbian people, originally from a place known as Aztián, arrived in the Valley of Mexico. They called themselves Mexitin or Mexica and it was the Spaniards who gave them the name Aztecas in reference to their place of origin.

The founding of Tenochtitlán, present-day Mexico City, is in itself quite interesting. According to the legend, the tribal god Huitzilopochtli ordered the Mexicas "to set up their camp at the place where they saw an eagle perched on a cactus tree and devouring a snake". The omen (which is now the emblem of Mexico and features on the national flag) revealed itself on an island in the middle of a lake, and one of the largest agglomerations in the world was thus born.

Figure 17.3 – The Aztec city of Tenochtitlán (future Mexico City)

From a symbolic point of view, the snake is often used by pre-Hispanic people as a representation of volcanoes and earthquakes. To settle on an island, away from volcanoes and with soft ground capable of dampening seismic waves (only of course for rigid constructions) seemed undoubtedly a "functional" choice if the idea was to "defeat the snake". Besides, the expansion of the Aztec empire proceeded on the back of the military defeat and taxation of subjected tribes, and an island on a lake was, military speaking, a strategic location.

When Hernán Cortés landed in 1519, the Aztec empire was vast but also widely reviled. Cortes was a warrior, and a merciless one at that (he is said to have been responsible for the between 15,000 and 30,000 deaths at the Cholula massacre near Puebla, a sad episode still vividly remembered in Mexico), but he certainly did not lack political and diplomatic skills. In fact, he could never have conquered Mexico with a handful of men if he had not been able to forge a series of pacts and alliances with a number of indigenous groups. He himself took an Amerindian mistress, "La Malinche", later to be known as Doña Marina, who was a former slave given to the conquistadors by a Maya chieftain and who acted as an interpreter and an adviser to Cortés. She bore him a son and Cortés is often quoted as saying that, after God, Marina was the key reason for his success.

Relying on the unwavering support of the Tlaxcaltèques, and rallying all the enemies of the Aztecs, Cortés finally conquered Tenochtitlan on August 13th 1521 after a three-month long siege and fighting that caused the destruction of part of the city. Estimations of casualties vary greatly but between 120,000 and 240,000 Aztecs are said to have died, 40,000 of these in combat. To secure his power, Cortés had to take the capital of the Aztec empire and make it his own. The winners being the name givers, Tenochtitlán became Mexico and the Mexicas were renamed Aztecas, but the location remained the same. Mexico became the capital of the New-Spain, temples were razed to the ground and churches built in their stead, and it is estimated that at the start of the 17th Century the population of the town was 200,000 strong, only 2,000 of whom were Spaniards.

Figure 17.4 – «The consecration of the pagan temples»

Figure 17.5 – Mexico in1628

When it came to dealing with natural hazards, however, the Spaniards were less successful in controlling the hydraulics than the Aztecs. They fell victim to several floods during the 16th Century and in September 1629 "el diluvio" (the deluge) struck. This flood was one of the most tragic natural disasters in the history of Mexico. Thirty thousand people were drowned and the survivors had to struggle through a series of epidemics in its wake. It was not until 1634 that the floodwater finally retreated from the town and for a time it was believed that the site should be abandoned. Eventually two responses were adopted: one religious and the other civil. As was customary at the time, Church and society interpreted this catastrophe as a divine punishment; The City of Mexico had surrendered to sin and it had to atone. The inquisition went to work and proceeded to burn at the stake Marranos (Jews recently converted to Catholicism), sodomites, and Portuguese for good measure. The civil response, civil engineering that is, was just as simple (as engineering solutions often are!) but more effective all the same: To prevent flooding, the lake just had to be emptied. And so it was done, although the effort was colossal (as is often the case when implementing "simple" engineering solutions!), and it would take over two centuries for Mexico City to cease being an island and become a town whose soil became inexorably more compacted.

Figure 17.6 – Mexico City in the 17th Century

Figure 17.7 – Mexico in1796

As the lake was emptying, Mexico City was not spared from earthquakes. There are recorded events (1568, 1611, 1653, 1682, 1697, 1711, 1768, 1787, 1800, 1806, 1837) for which seismologists are able to provide a location, magnitude and intensity maps. However, because of the low building heights, the damage always remained limited and the chronicles do not speak of major catastrophes for the town itself.

During the 20th Century, the town experienced tremendous expansion. From 350,000 inhabitants spread over 27 km2 in 1900, it grew to a population of 1.8 million over 117 km2 in 1940, to reach 18 million over 1,540 km2 in 2000.

But seismic risks remained quite low on the list of preoccupations. The first event to shake the “modern” city occurred in 1941 and led to the 1942 regulations, the first regulations for the federal district of Mexico to provide guidelines regarding seismic design.

The second alert took place in 1957. This time it had a powerful symbolic dimension: the Angel of Independence, the statue by Antonio Rivas Mercado erected in 1910 to honor the heroes of the struggle against Spanish domination, was toppled. The symbol of Mexico City lay on the ground.

A new standard was introduced in 1957, then another one in 1966, and again in 1976. But since only 70 inhabitants had lost their lives during the 1957 event, the risk was not to the forefront of public consciousness and the standards were only applied to new buildings without much concern for pre-existing structures.

Then, at 07:17 on September 19th 1985, Mexico City was struck by what will be remembered in the records as “the hammer blow”: at least 10,000 people died and 2831 buildings were damaged, 258 of which were totally destroyed and 143 partially collapsed. Such figures were previously unheard of and Mexico City was expected not to recover quickly.

However, with a show of incredible vitality, Mexico City confronted the disaster once more and did indeed recover. The most powerful symbol was perhaps the 1986 football World Cup which took place in Mexico. Argentina won the competition, but Mexico will probably be remembered in history as the true winner for the post-earthquake organization of this World Cup.

Figure 17.8 – Mexico City 1985 «the hammer blow»

Figure 17.9 – The World Cup, Mexico 1986

In the wake of this earthquake emergency, anti-seismic standards were introduced in 1985. In 1987 standards were issued regarding foundations. The last prevailing standards are the NTC 2004. Following the 2017 earthquake, these “modern” standards were deemed satisfactory. They will certainly be improved, refined and adjusted, but their complete overhaul is not envisaged. It should also be noted that, thanks to the “modern” standards, quite audacious buildings have been erected. The Torre Vireyes, which towers 130 m in height and which was built between 2011 and 2015, is a good example.

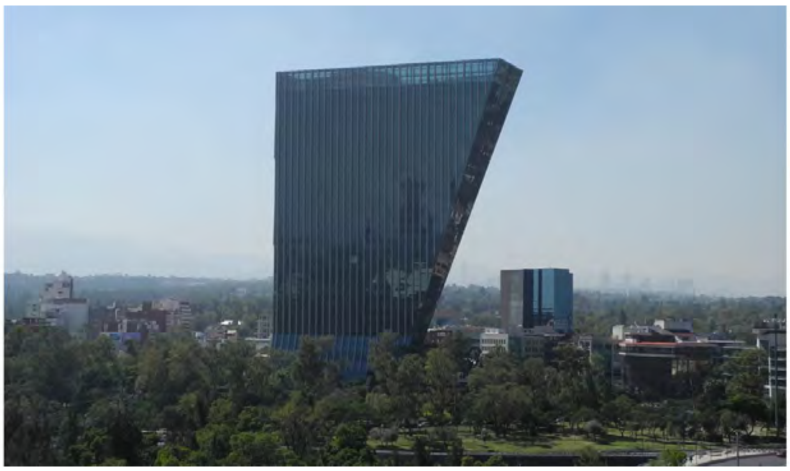

Figure 17.10 – La Torre Vireyes

At the beginning of the 21st Century, the word “resilience” started to appear in discussions concerning urbanism[12] . In 2013, Mexico City joined the «100 Resilient Cities», a group created at the initiative of the Rockefeller foundation (a foundation that never fails to flag its interventions). But, marketing and communication apart, it is positive to note that the seismic risk features high on the list of perceived risks for Mexico City in a 2016 brochure, i.e. just before 2017.

Figure 17.11 – Mexico City 2016 «The strategy of resilience» (as seen by the Rockefeller Foundation)

Thirty two years to the day after the 1985 earthquake, at 13:34 on September 19th 2017, just after the “Simulacro 2017” had finished, another earthquake struck. The results were tragic, with buildings collapsing and people dying. But, with hindsight, one realizes that the scale of this disaster is in no way comparable to that of the 1985 event. And yet, the 2017 earthquake was no less impacting than the 1985 one. The areas affected were not exactly the same but buildings that had withstood the 1985 earthquake collapsed completely in 2017.

Between 1985 and 2017, in the space of one generation, tremendous work has been accomplished in all sectors (scientific studies, regulations, retro-fitting, exercises, etc.) and it can be said that this work has been effective. Certainly there are still gaps and shortcomings in the measures, in particular regarding the vulnerability of structures completed before 1985, and the process must continue (and no doubt it will). However, it appears that in Mexico City in 2017, the seismic risk has become a manageable risk, a formidable achievement for an agglomeration of this size.

Mexico City 1985-2017: an enormous difference. In the face of earthquakes, tragedy is no longer inevitable, thanks to the efforts of the earthquake engineering community as a whole.

If the football world cup was Mexico City’s answer to the 1985 earthquake, in 2017 one could choose as the symbol of the city’s post-earthquake vitality the construction of the new airport, designed by architects Norman Foster and Fernando Romero. In fact, the latest events did not slow down the construction of the airport, where soil compaction operations of gigantic proportions are underway. As one browses through the new airport presentation documents, it is fitting to come across two Toltec warriors, acting as two Atlas figures within this ultramodern project. It proves that Mexico remains true to its past and its ancestors, who were already familiar with the management of seismic risks.

Figure 17.12 – Mexico City new airport with its two Toltec warriors (designed by Norman Foster and Fernando Romero)

Finally, while the seismic risk to Mexico City can now be deemed manageable, other natural hazards remain: in particular, the volcanic risk that constantly threatens the town. During our visit to the Centro Nacional de Prevencion de Desastres, we observed a color-coded scale on a poster indicating the volcanic risk: green for «normal», orange for «alert», and red for «alarm». A code red alarm would entail a “complete evacuation of the population”. On the scale of such an agglomeration, a complete evacuation is no small feat. Our reflections on urbanism in the face of natural risks for the city of Mexico are therefore far from complete.

[12] This word comes from physics. Resilience characterizes the resistance of a material to shocks. It originally conveyed the idea of springing back or bouncing; a rather playful word.

18 Conclusions

We embarked on this mission with four main questions to answer:

- What was the impact of the 2017 earthquake on Mexico City compared to that of 1985?
- Did the more recent buildings, constructed after 1985, behave adequately?
- Did buildings retro-fitted since 1985 behave adequately?
- How did French buildings in Mexico City, rebuilt or strengthened since 1985, behave?

The first question deserves a nuanced answer. The September 19th 2017 earthquake was of a lesser magnitude (Mw 7.1) than the September 19th 1985 event (Mw 8.1), but it was much closer to Mexico City (120 km distant in 2017 as opposed 350 km in 1985) and its focus was deeper (51 km deep in 2017 as opposed to 33 km in 1985).

Consequently the effects were different. The zones of greatest damages were not the same for both events: In 2017, damage was concentrated In the "transition zone" on the shores of the former lake, whereas in 1985 most of the damage was concentrated at the center of the former lake.

Some buildings that had withstood the 1985 earthquake suffered total collapse in 2017.

Based on these observations, we can conclude by saying that the 2017 earthquake was probably more localized in its destructive effects than that of 1985, but it was by no means less impacting for the city of Mexico.

It should also be remembered that no two earthquakes are the same and that past resistance does not necessarily ensure resistance to future events.

Regarding the second point, which deals with recent buildings, we should mention that, apart from three or four exceptions, all buildings that collapsed in 2017 had been constructed before 1985 (and had not been strengthened since). Conversely, we can infer that most buildings constructed after 1985 behaved adequately.

While building codes and calculation rules were modified after the 1985 earthquake in Mexico (and the world over), no significant change in the regulations is envisaged in the wake of the 2017 event.

Certainly, some improvements will be made, such as the recognition of evolution in time, or refined zonings, but broadly speaking, one can say that the corpus of knowledge on this topic is now fairly well established.

This lesson, we believe, is essential for the earthquake engineering community. Throughout the 20th Century, major earthquakes were systematically followed by changes in the rules and codes. Now, at the beginning of the 21st Century, this is no longer the case, and the existing regulations can be regarded as satisfactory.

It remains, however, for the regulations to be applied everywhere, but this is another issue.

Regarding the third point, the mission did not observe any significant damage to buildings retro-fitted after 1985. This is an important finding for the earthquake engineering community.

Obviously it is possible to retro-fit, strengthen or rigidify existing buildings in a reasonable manner so as to ensure that they behave correctly during an earthquake.

There are of course several ways to proceed and one should not restrict the reinforcement techniques to one single "one-size-fits-all" solution. With this in mind, the examples in Mexico City offer us a palette of effective solutions (solutions that have been tried and tested under real earthquake conditions).

Regarding the fourth point concerning the behavior of French buildings in Mexico City, here also the findings are clear: the mission did not observe any significant damage to any of the French buildings in Mexico City.

We have to commend the building management policy initiated by France in Mexico since 1985. We express the hope that the same policy of preventive management of seismic risks will be implemented in all earthquake-prone cities across the world where France is represented.

In the framework of this mission, we were able to answer, quite clearly, the four questions originally asked.

But we have also been able to widen our observations to encompass other topics:

- The important role of emergency post-seismic diagnostics, a field in which the AFPS is already involved and that must be developed further,
- The benefits arising from mastering the use of geographic information systems, a field still in its infancy for us but that deserves to be developed and put into use,
- The issue of historic buildings, which require specific approaches and which should be further considered in collaboration with experts in the field.

The conclusions we draw from this mission are quite positive. The numbers speak for themselves: over 10,000 victims in 1985 and only about 300 in 2017 for an earthquake admittedly different but not necessarily less impacting.

Of course every earthquake is a tragedy with dreadful collapses, injuries, deaths, all deservedly echoed in the media..

To put the 10,000 deaths of 1985 and the 300 of 2017 in context for a population ranging in the millions of inhabitants:

- In 1985 road accidents in France caused the deaths of 10,000 people, and we are still nowhere near reducing that to 300 deaths today (in fact it is of the order of 4000),
- In 2009, the L'Aquila earthquake, with magnitude Mw of 6.2, caused the deaths of about 300 people for a population of approximately 70,000 inhabitants,
- In 2016, the Amatrice earthquake, with a magnitude Mw of 6.0, also caused the deaths of 300 people but, more tragically, for a population of only about 3,000 inhabitants.

Seismic risk management at the scale of a major agglomeration is therefore an achievable objective, even over a relatively short timescale (30 years!).

This risk management does not stand in the way of architectural quality or urban development. The Mexico City example proves, in fact, the opposite is true, as anti-seismic constraints push architects to explore new and more creative avenues and force town planners to opt for a more controlled structuring of towns.

One last point we would like to raise involves the benefits to be gained from post-seismic missions in the field.

In 1985, the findings of the AFPS mission were very significant for the whole earthquake engineering community.

In 2017, we were able to observe at first hand some of the positive outcomes of the procedures initiated more than thirty years previously. If instead we had stayed away and only observed Mexico City remotely through the prism of the internet or the magnifying glass of the media, we would undoubtedly have had a distorted view of things and missed many very pertinent aspects.

Finally, we hope that in another thirty years' time this report can be the cornerstone for a new mission to Mexico City.

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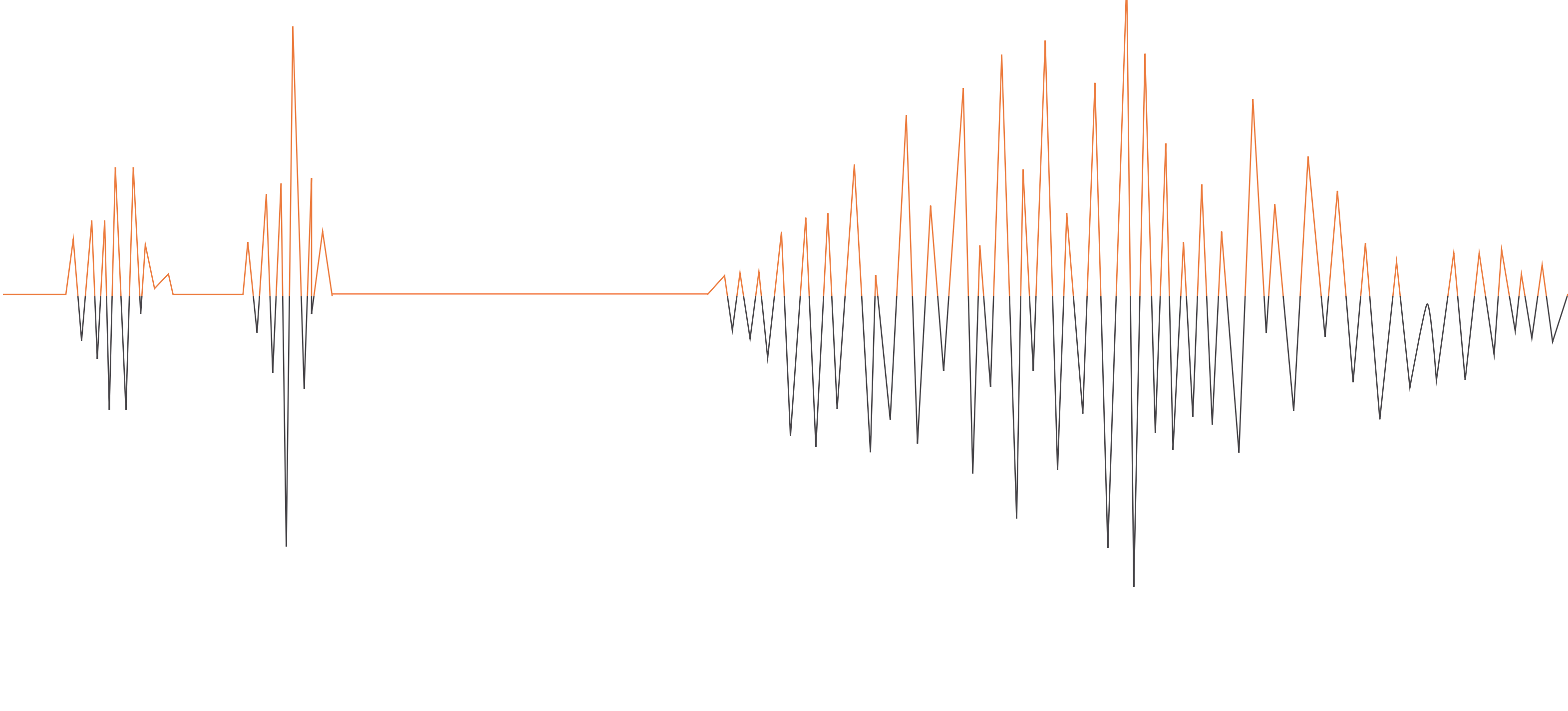

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