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Geoscience Aspect of September 19, 2017 Mexico Puebla-Morelos Earthquake

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ABSTRACT

Compared with the M_w8.0 Michoacan interplate event that occurred on the same calendar date 32 years ago, the recent M_w7.1 intraplate event had less impact both in affected areas and in severity. The roles played by the ground motions, site setting of the Mexico City and structural types of affected building stocks on earthquake damage shared similarities in the two events (see Table 1). This paper attempts to highlight how the interplay of the above three key factors was manifested in the observed damages. It further discusses the significance of this intraplate event to the Mexico City itself as well as to other cities sharing its physical setting and presence of vulnerable building stocks. While the problem of ongoing ground subsidence due to extraction of groundwater in the Mexico City is widely recognized for decades, the somewhat related problem of ongoing ground cracking and its intensification during seismic events has only recently been studied systematically since 2005. The manifestation of this problem in 2017 is described and discussed in the paper. The Mexico City has coped with its multi-faceted problems: serving its population of approximately 21 million in normal time as well as meeting its emergency challenges during seismic events. There is much to learn from our Mexican colleagues. The paper concludes with a summary of key lessons we learned from this recent earthquake, including the application of earthquake pre-warning system during the event.

INTRODUCTION

A series of earthquakes rocked the central valley of Mexico in September 2017, including two largest intraplate events, M_w8.2 event on September 8 and M_w7.1 event on September 19, within the subducting Cocos plate. The M_w7.1 event being closer to Mexico City had a greater impact on the capital. The authors, as part of a 7-member Canadian post-earthquake reconnaissance team, visited Mexico City and its vicinity from October 15 to 21, 2017. The paper draws from our site observations as well as reconnaissance reports by the host country [1], USA [2 to 5] and Japan [6]. An overview of structural performance is presented in a companion paper by Saatcioglu et al. [7], while the geoscience/geotechnical aspect of this earthquake is covered in this paper.

Mexico City Seismo-tectonic setting

The bulk of Mexico is located over two large tectonic plates: North America and Cocos plates. This is one of the world's most active seismic regions. The Cocos plate moves northeastward and subducts under the North America plate along the Middle America trench. The rate of plate convergence in the area ranges from 63 mm to 76 mm per year. Due to this convergence, the Mexican land mass is crumpled to form the Cordillera Neovolcánica mountain ranges of southern Mexico. As the Cocos plate subducts, it melts. The molten material is forced upward through fractures in the overlying North America plate. The process has caused frequent earthquakes and occasional volcanic eruptions [8] (see Fig. 1). Popocatépetl and Ixtaccíhuatl volcanos ("Smoking Mountain" and "White Lady," respectively), southeast of Mexico City, can be seen from the City in clear weather. From 2004 to 2018 (ongoing), Popocatépetl renewed its activity causing seismologists and government officials to be concerned about the potential effect of a large-scale eruption on the heavily populated region.

Seismic events affecting Mexico City include: crustal events within the upper North America plate [9], intraplate events within the lower Cocos plate [10] and the interplate events at the interface between the two plates [11]. The September 19, 2017 earthquake occurred as a result of normal faulting at a depth of approximately 50 km. It involved a rupture plane of about 50 km long and 20 km wide. Over the preceding century, the region within 250 km of the hypocentre experienced 19 other M 6.5+ earthquakes. Most occurred near the subduction zone interface at the Pacific coast, to the south of the September 19 event.

West coast of Canada shares a similar seismo-tectonic setting as the southern Mexico region, with the subduction of the Pacific ocean plate and smaller Explore and Juan de Fuca oceanic plates along the Cascadia fault under the overlying North America continental plate. The plate convergence rate near Victoria/Vancouver is, however, 40 mm per year, about half of that in the southeastern Mexico region. In the National Building Code of Canada, seismic hazard along the west coast of Canada does include the consideration of the above tectonic similar setting.

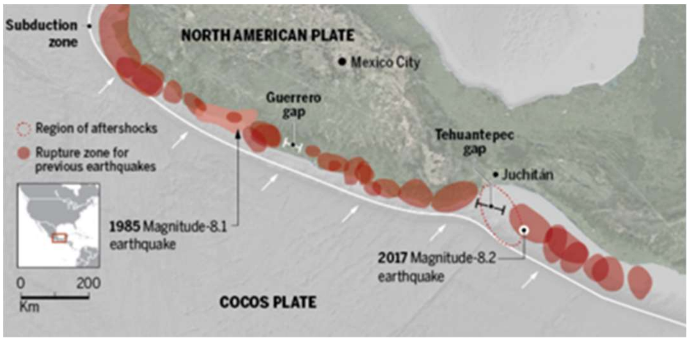


Figure 1. Cocos Plate Subduction zone. Credits: (Graphic) G. Grullón; (Science Data) V. Kostoglodov Mexico National Seismological Service

Table 1. Comparison of Earthquake and Damage Data – September 19, 1985[1] vs 2017[2] Earthquakes

Date (Local Time)	Earthquake Location	Type	Focal Mechanism	Peak Acceleration Intensity, MMI	Special Features	Casualties	Damages		General References
							General	Lifelines	
1985 Sep 19 (7:17:47)	Michoacan, Mexico	Interplate	Mw 8.0, Depth 27.9 km Thrust eq.	In general MMI up to VII in coastal area, and up to VI in Mexico City, but in localized zones MMI up to VIII- IX in coastal area, and up to IX-X at mouth of Balsas River, and up to VIII-IX in Mexico City	The event caused significant improvement of building codes in Mexico as well as many other countries including Canada and USA	Very High death ~9,500+ injured ~30,000 displaced >100,000	Cost of damage ~3 to 4 billion US dollars, 412 buildings collapsed and 3,124 buildings seriously damaged in Mexico City.	Damage and collapse of SCT Communications building (causing disruption of long-distance telecommunication over 3 weeks) and several medical facilities and school buildings	USGS[1] Mitchell et al. 1986
2017 Sep 19 (13:14:38)	Puebla, Mexico	Intraplate	Mw 7.1, Depth 48 km Normal eq.	Up to VI – VII in Mexico City	Ground cracking causing significant damages in buildings, roads, water/sewer lines in Colonia Del Mar and Cienega San Gregorio of Mexico City	Low death: ~220+ in Mexico City 142 in other cities injured ~6,000	44+ buildings collapsed, many others damaged in Mexico City, many collapsed and damaged buildings in other cities	Significant damages in electric grid, water and sewer lines (particularly in Colonia Del Mar) of Mexico City, some collapsed and damaged bridges in other cities	USGS[2] GEER 2018

Notes: 1. https://earthquake.usgs.gov/earthquakes/eventpage/usp0002jwe/executive
2. https://earthquake.usgs.gov/earthquakes/eventpage/us2000ar20/executive

Lacustrine sediments in the Mexico City basin

The widespread presence of lacustrine deposits in the Valley of Mexico basin, including Mexico City, as well as local engineering practice dictates the foundation problems encountered by structures in the city. These problems include: regional ground subsidence and differential settlement of buildings. During seismic events, the relatively soft lacustrine deposits tend to amplify ground motions, increase site natural periods and lengthen the duration of shaking. II.UNAM [12] provides a comprehensive background of this unique issue covering its development over a period of six decades from 1959 to 2016. The GEER [2] also summarizes the seismic aspects of this type of soil condition succinctly.

SEPTEMBER 19, 2017 EVENT

Ground motions and site effects

The 1976 Mexican building code initially defined 3 seismic zones for Mexico City: the hill zone (zone I), the transition zone (zone II), and the lake zone (zone III). The zones are defined based on the fundamental site period which is essentially a function of the thickness of soft lacustrine clay. The latest version of the building code [13] further divides zone III into 4 sub-zones (IIIa, IIIb, IIIc, and IIId, see Figs. 2 and 3). Throughout Mexico City, the thickness of lacustrine clay varies from 0 m in the hill zone (zone I) to about 60 m in zone IIId, with the fundamental site period varying from about 0.5 sec to 4 sec.

The Colegio de Ingenieros Civiles de México (CICM) website www.sismosmexico.org presents the geographical distribution of building damages in Mexico City, as shown in Figs. 2 and 3. The distribution of six geo-zonations is also shown on the figures. Damaged buildings shown by the red symbols in Fig. 2 are deemed unsafe for occupation following the September 19th earthquake, while those shown by the black symbols in Fig. 3 represent collapsed buildings. The majority of collapsed and damaged buildings are located in the western portions of the transition zone (zone II), and the two lake subzones with smaller clay thickness (zone IIIa and IIIb). It is interesting to note that only a handful of buildings in zone IIId, where the lacustrine clay thickness is greatest, were damaged and none of them collapsed.

Ground motion recordings

Raw earthquake recordings were provided by the Centro de Instrumentacion y Registro Sismico (CIRES, cires.org.mx). A total of 61 records were retrieved from the recording stations located in six seismic zones in Mexico City (see Fig. 4). Figure 5 shows the map of peak ground acceleration (PGA) in (cm/s^2). Table 2 presents the average properties of these stations in each seismic zone. These raw recordings were filtered in order to calculate acceleration, velocity and displacement response spectra for all three components of ground motion. The following section presents results of detailed analysis by Yniesta [14].

Figure 6 presents selected response spectra for each zone. The selected spectra are representative of the average spectra observed over a given zone, with the exception of Fig. 6a for the hill zone (I). The spectra in Fig. 6a is larger than the average spectra in the hill zone. One of the takeaways from Fig. 6 is that the frequency content of the motion spectrum changes when going through zones of increasing softness. The larger spectral response is observed at greater periods in the softer zone, which is to be expected. However, the spectral acceleration for these zones is relatively low.

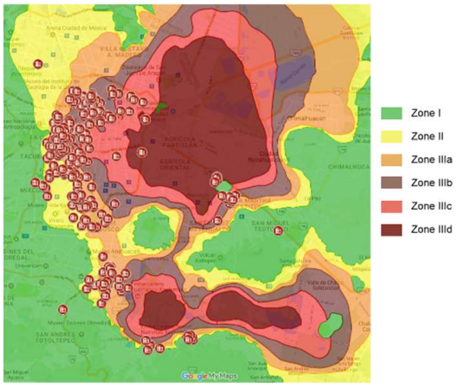


Figure 2. Map showing buildings deemed unsafe for occupation https://www.sismosmexico.org/mapas

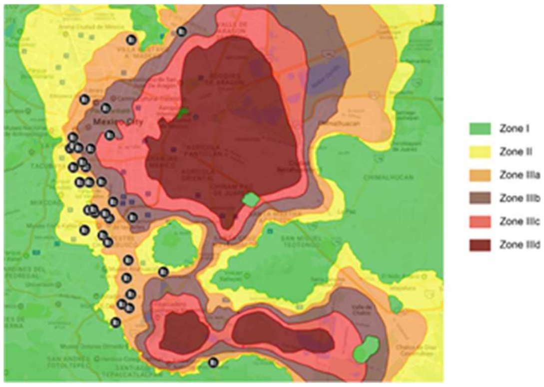


Figure 3. Map showing collapsed buildings https://www.sismosmexico.org/mapas

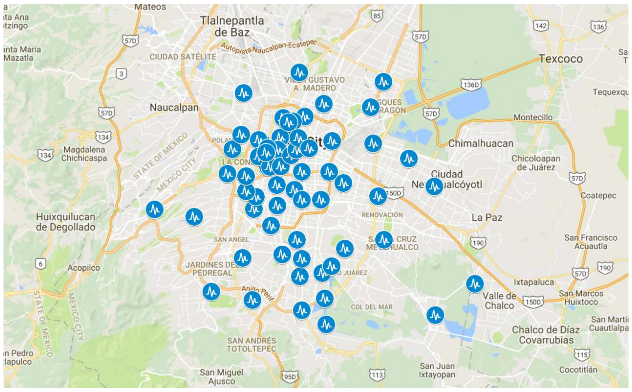


Figure 4. Location of recording stations https://www.sismosmexico.org/mapas

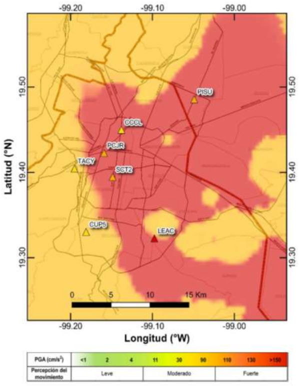


Figure 5. Map of PGA (cm/s^2) during the Sep. 19, 2017 earthquake (from II.UNAM 2017)

Note that the frequency content of the vertical acceleration spectra is essentially independent of the softness of the zone, in part because it is relatively low, and in part because the response of the soil to the vertical motion is essentially linear [15]. The elongation of spectral mean period and the large response observed in zone II (and IIIa to a lesser extent) is due to the effect of soil response on the propagation of seismic waves.

The shift in frequency content at all sites is consistent with the response spectra presented in Fig. 6. The frequency content of the response spectra is of interest because it defines the motion transmitted to the buildings located on the subsoil. Most of the buildings that collapsed were 7-10 storey high, and were associated with a fundamental period of about 1.0 sec. The motions in zones II and IIIa had predominant spectral period of about 1.0 sec, and had the highest spectral acceleration, which would affect specifically this type of buildings.

Table 2. Ground motion recording station average properties

Zone	Average V_S (m/s)	Average Site Period T_s(s)	Number of recording stations
I	117.4	0.43	7
II	115.1	0.52	9
IIIa	94.2	1.05	8
IIIb	82.8	1.73	15
IIIc	81.8	1.96	12
IIId	81.8	2.26	10

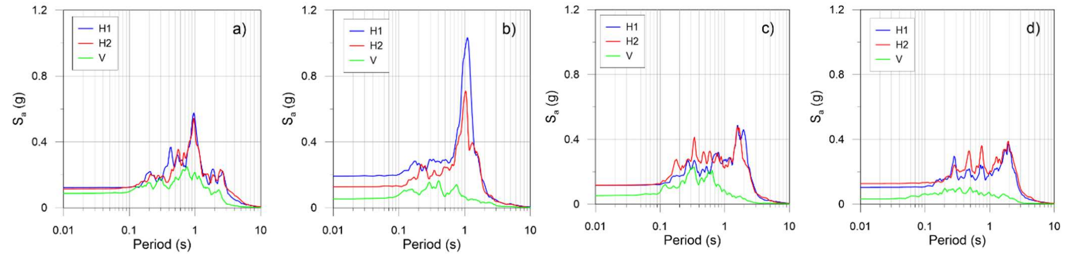


Figure 6. Acceleration response spectra (5% damped) at recording station: a) MY19 (Hill zone), b) DX37 (Transition zone (II)), c) CI05 (lake zone (IIIa)) and d) PE10 (Lake zone (IIId))

GEOTECHNICAL PROBLEMS AND TYPICAL BUILDING FOUNDATIONS

Subsoil conditions

Mexico City is located in the Valley of Mexico, which before the completion of the Nochistongo drainage cut in 1789 was a closed basin containing numerous lakes. These had been partially filled by alluvium and clay derived from weathered volcanic rocks. The original city was built on the location of the old Aztec capital Tenochtitlan [16] (see Fig. 7c), which was established on an island in Lake Texcoco with three causeways connected to adjacent lands. As Mexico City grew, it expanded from the old island, across the former lakebed, and onto the surrounding hills. To cope with the vast differences in subsoil conditions, it was necessary to divide the city into three zones for seismic design purposes: the foothills or firm ground zone, the transition zone, and the lake or soft soil zone (see Fig. 7a). Subsoil in the foothills zone is lava or very competent soils, while subsoil in the lake zone includes the upper and lower clay layers having water contents of about 300% and 200%, respectively. Geotechnical problems associated with Mexico City clay are regional subsidence (up to 9 m) due to groundwater withdrawal, building settlements, subsoil disturbance due to adjacent foundation construction, and severe earthquake shaking. Earthquake damage zones in the 1957, 1979, and 1985 earthquakes are shown in Fig. 7b.

Foundation practice in Mexico City

Typical foundations adopted in Mexico City are illustrated in Fig. 8. Light structures are usually founded on shallow footings of masonry (see Fig. 8a) or concrete that are sometimes interconnected by grade beams. In order to mitigate settlement problems for larger structures, "floating" or, technically more correct, "compensating" rigid-box foundations are used to compensate for the building weight (see Fig. 8b). End-bearing piles (see Fig. 8c) are used for heavier structures. This, however, could cause the ground floor to be above grade as the surrounding ground settles.

Friction piles (see Fig. 8d) tend to mitigate this problem, because the piles settle with the supporting soil. Interlaced piles (see Fig. 8f) stiffen the supporting soil and therefore exhibit a behaviour somewhere in between that of end-bearing and friction piles. End-bearing “control piles” (see Fig. 8e) transfer the building weight through compressible cushions that have design load-deformation characteristics that would permit the structure to follow the ground settlements in a controlled manner.

Figure 9 shows the photo of such an installation, which would require periodical adjustments of the control elements to harmonize settlement of the structure with that of the surrounding ground. The famous Latin American Tower (La Torre Latinoamericana) has both end-bearing piles and a “compensating” foundation, designed by Zeevaert [17, 18]. The tower performed very well during both the 1985 M_w8.0 and the 2017 M_w7.1 earthquake. Many buildings in Mexico City become tilted due to differential settlement caused by static or seismic loading. Valenzuela-Beltrán et al. [19] looked into additional strength requirement for asymmetric yielding of this type of buildings, and recommended code-related provisions for their seismic design.

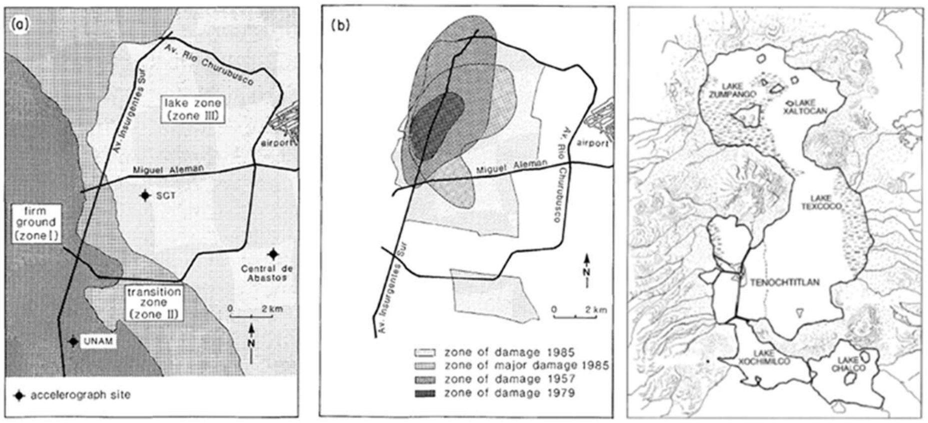


Figure 7. (a) Subsoil zones of Mexico City, (b) damage zones in the 1957, 1979, and 1985 earthquakes and (c) City of Tenochtitlan (modified from Mitchell et al. 1986 and Sabloff 1997)

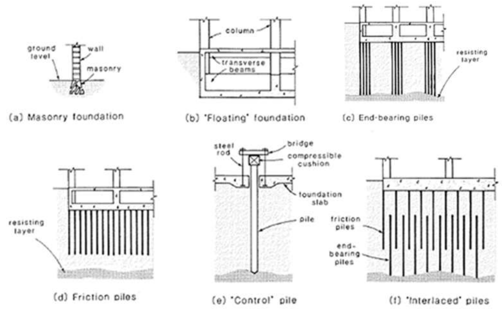


Figure 8. Foundation types used in Mexico City (from Mitchell et al. 1986 and Marsal 1975)

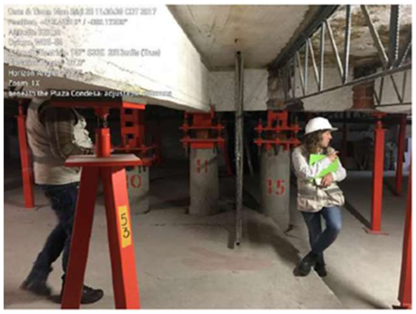


Figure 9. End-bearing control piles supporting the La Plaza Condesa building (Fig. 4.27 of GEER 2018)

Ground failure observations

GEER [2] covered slope instability extensively including rockfall, deformation of natural slope, embankment and bridge abutment. Representative photos of our site observations with reference to GEER [2] are given below:

- Slumped canal masonry side wall (Fig. 10) – The masonry side wall, covered with a wire mesh, performed well in general except a local slumped segment. The wall segment repair was in progress. It appeared that a cofferdam was being built probably for dewatering purposes during replacement of the failed segment.
- Slumped low masonry retaining wall (Fig. 11) – The original hill slope of Xochimilco appeared to have been re-configured by cut- and-fill to fit in three-levels of roads: at the base, 1st and 2nd level along its perimeter. Masonry walls were used to retain soil on the uphill side of the roads. The hill slope was reported to undergo deformation during the 1985 earthquake, and continued to deform slowly prior to the recent seismic event which intensified the movements. Longitudinal cracks were formed along the 1st and 2nd level road; cracks at the 2nd level road were much shorter. The masonry wall shown in Fig. 11 was at the 1st level road; new masonry materials were stockpiled on the ground, and the distant end segment of the wall was shored up by timber struts. Drill rigs were observed at the base and 1st level road, indicating subsoil investigation was in progress. The ongoing operation of a water-well pump station at the base level with observed settlements, cracks and formation of voids in the vicinity is considered to be related to hill slope movement [2].
- Existing ground cracks were accelerated during the 2017 seismic events in Colonia Del Mar [2] and Cienega San Gregorio of Mexico City. Photos taken in Cienega San Gregorio are shown in Figs. 12 and 13. The area is an agricultural district with vegetable-flower fields and nurseries. Figure 12 shows an elongated crack passing through a covered nursery and open field all the way to the adjacent property. Figure 13 shows a slumped and repaired segment of a causeway. The slumped segment underwent lateral spreading failure involving soft lake deposits beneath the granular embankment fill. The repair was carried out by bulldozers and dump trucks using granular fills borrowed from nearby quarries.

Figure 10. Slumped canal masonry side wall

Figure 11. Slumped masonry retaining wall

(a) Ground cracks inside a nursery *(b) Cracks extended to open area outside*

Figure 12. Ground cracks developed in a nursery extended all the way to neighbouring property

(a) Failed causeway segment *(b) Repaired causeway segment*

Figure 13. Causeway embankment failed by lateral spreading

EARTHQUAKE EARLY-WARNING SYSTEM

Historical development

The September 8th, 2017 (UTC time) M_w8.2 earthquake originated from the southern end of the subduction zone near the Tehuantepec Gap. The Guerrero gap remains a major seismic threat, as it has not been ruptured since the beginning of the 20th century (see Fig. 1). After the deadly 1985 Mw 8.0 interplate seismic event, the Mexican authorities enacted the law for Civil Protection to mitigate the consequence of future earthquakes.

Since 1987, the authorities have promoted the creation of an early warning system with the aim of reducing human loss in future earthquakes. The principle of such a system is, following the detection of a large earthquake by strong motion accelerometers, to send an alert to the main population centres before the actual arrival of seismic waves. The main immediate concern for the authorities was an interplate earthquake originating from the Guerrero gap, a zone situated 320 km from the Mexico City and capable of causing major destruction. This concern led the Mexico City Authorities to create the Sistema de Alerta Sismica Mexicano (SASMEX) in 1991. Thereafter this effort has been led by the Centro de Instrumentación y Registro Sísmico (CIRES). One of its responsibilities is to operate and maintain the network of recording stations. Initially only 12 stations were established as compared to more than 90 stations presently in operation. The system began operational in 1991, and has been available to public since 1993.

Since the main initial concern was an earthquake originating from the plate interface, the sensors were installed on the western coast as priority. While this is advantageous for early detection of large interplate earthquakes, it is less effective for detection of intraplate earthquakes which tend to occur further inland and more frequently.

Operating principle

When an earthquake is detected at a recording station, the system automatically estimates the magnitude of the earthquake based on an algorithm that correlates empirically the magnitude and the time of arrival of the primary P-waves. When the time of arrival of the secondary S-waves is determined, a different correlation is used to get a new estimate of the magnitude. A third correlation uses the time lapse between the arrivals of the P and S-waves to define the magnitude.

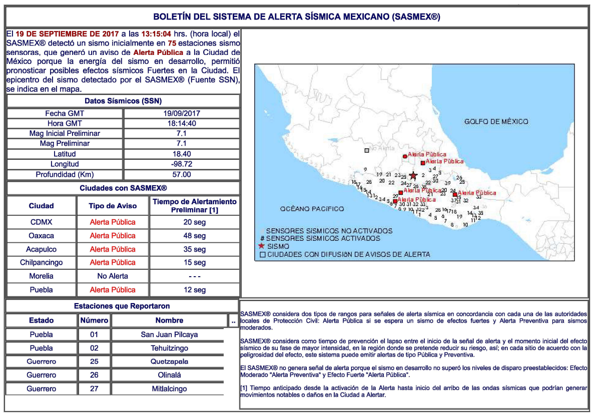
When a large earthquake is detected at one station, the system does not send an alert yet, rather it waits until the earthquake is detected by a second station for confirmation purposes. If the two magnitude estimates are inconsistent, the system remains silent until further confirmation from the detection at a third station. The expected magnitude is always re-evaluated when a new station registers the earthquake.

Since P-waves travel faster than S-waves, they are detected first. P-waves can be detected at a second station before the S-waves arrive at the first. In such a case, an alert can be triggered without any information on the S-waves. An alert is triggered only when the earthquake magnitude exceeds a threshold value of 5. Population centres situated too far from the epicenter to receive significant shaking will also not receive an alert.

Alerts are sent through a network of very high-frequency communication stations which can issue warning in two seconds or less [20]. In Mexico City, about 8,200 speakers are installed and emit an alarm when an earthquake is detected. In addition to speakers, alerts are also broadcasted on TV and radio. The CIRES also installs alert systems in buildings. Most of public schools are equipped with such a system along with fire stations and hospitals. The Mexico City Metro also receives SASMEX alerts, although they are used to stop trains, and not to warn commuters.

Performance during September 19th, 2017

The intraplate M_w 7.1 earthquake was first picked up by recording stations situated in the Puebla state. For this earthquake, all major population centres, except Morelia, were warned (see Fig. 14). Given the short distance to the epicenter, Mexico City was only given 20 seconds of warning before strong shaking occurred. The fact that only a few recording stations were located in the epicentral area contributed to relatively short warning time. Unfortunately, when the alarm went off in Mexico City, the low amplitude P-wave had already been felt. The warning siren also tends to be masked somewhat by the cacophony of urban noise. However, the successful execution of the early-warning system attests the due diligence of the agency in charge as well as the opportunities of frequent seismic events available to root out system shortcomings.



BOLETÍN DEL SISTEMA DE ALERTA SÍSMICA MEXICANO (SASMEX®)

El **19 DE SEPTIEMBRE DE 2017** a las **13:15:04** hrs. (hora local) el SASMEX® detectó un sismo inicialmente en **75** estaciones sismo sensoras, que generó un aviso de **Alerta Pública** a la Ciudad de México porque la energía del sismo en desarrollo, permitió pronosticar posibles efectos sísmicos Fuertes en la Ciudad. El epicentro del sismo detectado por el SASMEX® (Fuente SSN), se indica en el mapa.

Datos Sísmicos (SSN)	
Fecha GMT	19/09/2017
Hora GMT	18:14:40
Mag Inicial Preliminar	7.1
Mag Preliminar	7.1
Latitud	18.40
Longitud	-98.72
Profundidad (Km)	57.00

Ciudades con SASMEX®

Ciudad	Tipo de Aviso	Tiempo de Alertamiento Preliminar [1]
CDMX	Alerta Pública	20 seg
Oaxaca	Alerta Pública	48 seg
Acapulco	Alerta Pública	35 seg
Chilpancingo	Alerta Pública	15 seg
Morelia	No Alerta	- - -
Puebla	Alerta Pública	12 seg

Estaciones que Reportaron

Estado	Número	Nombre	..
Puebla	01	San Juan Pilcaya	
Puebla	02	Tehuitzingo	
Guerrero	25	Quetzapala	
Guerrero	26	Olinalá	
Guerrero	27	Mitlalcingo	

SASMEX® considera dos tipos de rangos para señales de alerta sísmica en concordancia con cada una de las autoridades locales de Protección Civil: Alerta Pública si se espera un sismo de efectos fuertes y Alerta Preventiva para sismos moderados.

SASMEX® considera como tiempo de prevención el lapso entre el inicio de la señal de alerta y el momento inicial del efecto sísmico de su fase de mayor intensidad, en la región donde se pretende reducir su riesgo, así; en cada sitio de acuerdo con la peligrosidad del efecto, este sistema puede emitir alertas de tipo Pública y Preventiva.

El SASMEX® no genera señal de alerta porque el sismo en desarrollo no superó los niveles de disparo preestablecidos: Efecto Moderado "Alerta Preventiva" y Efecto Fuerte "Alerta Pública".

[1] Tiempo anticipado desde la activación de la Alerta hasta inicio del arribo de las ondas sísmicas que podrían generar movimientos notables o daños en la Ciudad a Alertar.

Figure 14. Screenshot of the CIRES website summarizing the alerts sent on September 19th, 2017

CONCLUSIONS

The following summarizes some of the lessons we learned from this moderate earthquake event:

- Intraplate events, being more frequent and often closer to major urban centres than their headline-grabbing major interplate counterparts, are receiving more attention with time. Mexican earthquake early-warning system began in late 1980s, initially focusing on coastal interplate events. It has been improved and expanded to cover intraplate events, and has been available to serve the general public since 1993. Both Canada and USA are catching up; we look forward to further development of similar system along the west coast.
- The ongoing evolution of building code and related construction practice provide the public with minimum earthquake protection. Non-compliance of existing structures with current code is a difficult socio-economic issue. British Columbia has conducted a sustained program to upgrade school buildings for some time. This and other similar programs are important measures to remove and reduce the potential threat to life and property in the event of an earthquake.
- In seismic area, building renovation has to make sure that seismic upgrade is carried out by competent engineers/contractors, and inspected by regulators. Episodes of building partial and/or total collapse due to error, incompetence and other irregularities during this important phase are disheartening.

- Mexico City, with its frequent seismic events and unique subsoil conditions, and the ongoing structural deterioration of its building stock by repeated earthquake assaults, are both a concern and a tough issue to address. In some neighbourhoods, there are collapsed buildings sporadically distributed among similar buildings of same vintage, due to unfortunate combination of the given earthquake, site setting and structure make up.
- Perhaps, decentralizing Mexico City by relocating some governmental functions to locations with more competent subsoil than soft clay and less polluted air could be some food for thought for decision makers.

ACKNOWLEDGMENTS

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