Preliminary Statistics of Collapsed Buildings in Mexico City in the September 19, 2017 Puebla-Morelos Earthquake

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Abstract

On September 19th, 2017 a M_w7.1 intermediate-depth normal-fault earthquake occurred approximately 120 km away from Mexico City. The earthquake produced the collapse of 46 structures in Mexico City which resulted in 219 deaths. This was the most intense earthquake to hit Mexico City since the M_s 8.1 September 19th, 1985 earthquake. A preliminary study of the characteristics of collapsed buildings is presented. It is shown that most collapsed buildings had less than 10 stories and were primarily located in zones IIIa and IIIb of the microzonation of the 1987 Mexico City building code which are characterized by having total thickness of soft clay deposits between 25 and 40m and by predominant periods of vibration between 1s and 2s. It is shown that, although regions and building heights that were hit hardest were somewhat different than in 1985, there are many similarities in the characteristics of buildings that collapsed. Similarly to the 1985 earthquake, most of the collapse buildings consisted of reinforced concrete buildings whose lateral resisting system consisted of flat slabs supported by reinforced concrete columns. Collapses occurred primarily in buildings constructed prior to 1985, Furthermore, 57% of the collapsed buildings had a soft story. Both the flat slab and column lateral resisting system and soft stories have long been identified as building vulnerabilities. This highlights the need to possibly issue a mandate to evaluate and possibly seismically upgrade existing buildings located in the former lakebed of Mexico City that have these characteristics as they may be in danger of collapse in future earthquakes.

1. Introduction

Mexico has a long history of intermediate-depth, normal-faulting earthquakes within the Cocos plate. Some of them have caused extensive damage such as the 1931 M7.8 earthquake that produced major destruction in Oaxaca (Singh et al. 1985), the M~7.7 earthquake of 1958 which damaged some regions of Michoacán and Mexico City (Singh et al. 1996), the 1980 M7.0 earthquake which devastated Huajuapan de León, in Oaxaca (Yamamoto et al. 1984), and the M7.0 earthquake of 1999 which resulted in many damaged adobe dwellings in the region close to the epicenter and damaged colonial structures in the city of

Puebla (Singh et al. 1999; Yamamoto et al. 2002). Moreover, after the devastating M8.1 1985 Michoacán earthquake, the Mexico's Federal District building code was revised, explicitly incorporating intermediate-depth normal-faulting events (e.g., a M6.5 earthquake with a depth of 80 km was considered as representative of this group) when estimating the seismic hazard at Mexico City (Rosenblueth et al. 1989). More recently several studies have proposed ground motion prediction models specifically aimed at estimating ground motion intensities caused by intermediate-depth normal-faulting events within the Cocos plate in Mexico (García et al. 2004, 2005; Ordaz and Singh 1992; Pacheco and Singh 1995).

On September 19, 2017, at 13:14 local time (18:14 UTC), a moment magnitude 7.1 earthquake, with epicenter close to the limit between the states of Puebla and Morelos, struck the central region of Mexico, resulting in the collapse of 44 buildings, one pedestrian overpass, and one pedestrian bridge between two buildings in Mexico City. The event occurred at an intermediate depth of 57 km within the Cocos plate (which subducts under the North American plate) with an intraplate-normal-faulting mechanism characterized by a strike of 112°, 46° dip and -93° rake, according to the Servicio Sismológico Nacional (National Seismological Service of Mexico). The epicenter was located at 18.40°N and 98.72°W, 12 km southeast of Axochiapan, Morelos, and about 120 km from Mexico City. The closest distance from Mexico City to the rupture zone is approximately 105 km (Servicio Sismológico Nacional, 2017). The USGS locates the epicenter at 18.546°N, 98.487°W, and a depth of 51 km. They also report a normal-faulting focal mechanism with 108° strike, 47° dip and -98° rake (U.S. Geological Survey 2017).

A preliminary evaluation of the characteristics of the 44 collapsed buildings in Mexico City due to the M7.1 Puebla-Morelos earthquake is presented. A very brief history of earthquake resistant design codes in Mexico City is also presented in order to contextualize the collapse statistics. This report is based on available data gathered by in-situ reconnaissance by the authors between September 19th and September 24th, 2017 and complemented with information from other sources up to September 27, 2017.

2. Comparison of codes

The evolution of seismic design codes in Mexico City during 1957 and 1985 was strongly influenced by the M7.6 1957 earthquake which occurred at an epicentral distance of 256 km and several moderate intensity events which occurred on average every five years (Esteva 1987). The 1957 earthquake put in evidence the damaging effects that soft soil deposits in Mexico City can induce in certain types of structures, triggering the need of explicitly taking into account the soil type while computing the design forces in different regions of the city.

Figure 1 presents the microzonation that was included in the 1976 Mexico City code in which the city was divided into three zones according to local soil conditions: Hill zone, Transition zone, and Lake zone. This soil microzonation was commonly used in structural design prior to the 1985 Michoacán earthquake which demonstrated, once again, the need of a better characterization of soil types and of more stringent structural design requirements (Meli and Miranda 1985). This figure also shows with magenta markers the location of 44 collapsed structures caused by the 2017 Puebla-Morelos earthquake, which will be described in the next section. It is clear that collapsed occurred in either the Transition zone or the zone of shallower deposits of the Lake zone.

After early seismic codes in 1942 and 1966, in 1976 a new seismic design code was introduced in Mexico City, which recommended the use of a structural type and period-dependent reduction factors to compute design forces. It is worth mentioning that this code covered the analysis and design of flat slab systems which the 1985 earthquake proved it was extremely inefficient seismic lateral load resisting system. The main factor in the extensive damage and in large number of collapsed structures during the 1985 Michoacán earthquake was the large difference between relatively long-period spectral ordinates observed during the earthquake and design spectral values stipulated in the 1976 seismic code (Esteva 1987).

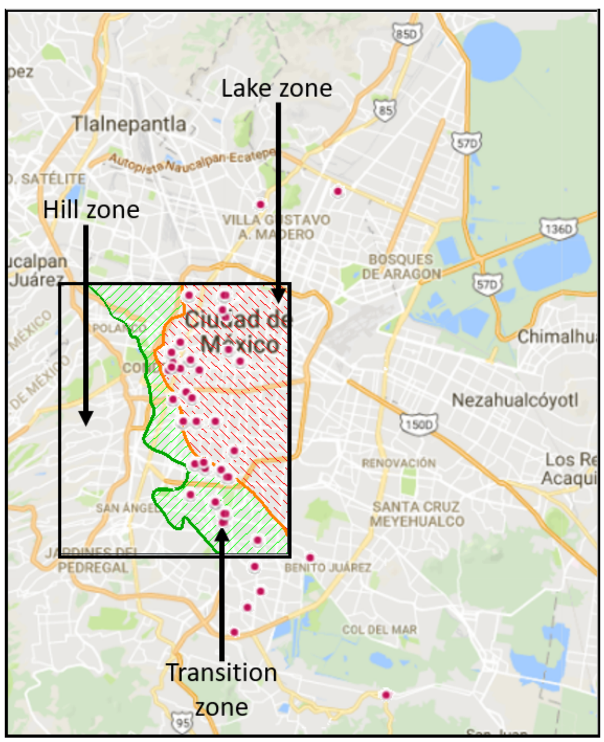
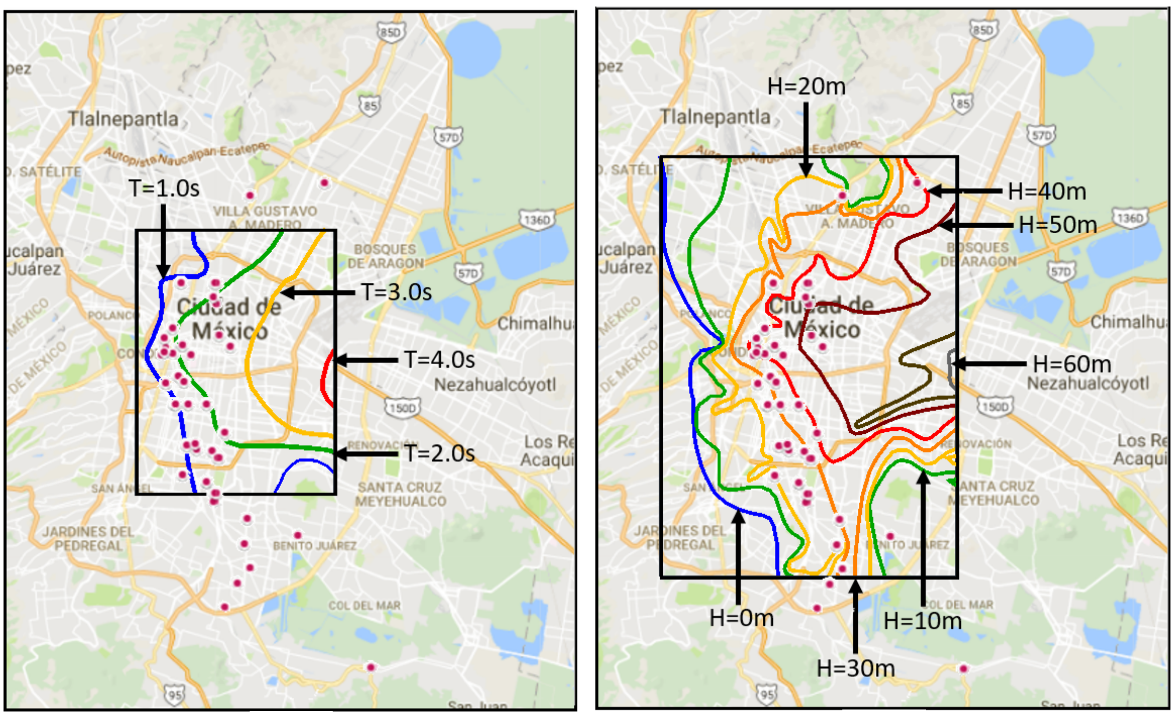


Figure 1. Microzonation of Mexico City in the 1976 code. Magenta markers indicate the location of collapsed structures during the 2017 Puebla-Morelos earthquake.

Following the 1985 Michoacán earthquake, a new version of the code was introduced in 1987 (NTCS-87 1987). This code included higher design spectral ordinates, more stringent criteria for structural analysis, structural members detailing, and construction quality and supervision. With regards to the design spectra, ordinates were increased by approximately 66% in the newly updated transition and soft soil zones which in combination of a decrease in reduction factors lead to design forces two to 2.5 times larger than those used in the 1976 code for structures in these two zones. In order to include soil-structure interaction effects in the structural design of certain structures, the 1987 code included isoperiod and clay deposit isodepth curves for Mexico City (Gómez and García-Ranz 1988). This information is presented in Figure 2(a) and 2(b) along with the markers that indicate the location of collapsed structures during the 2017 Puebla-Morelos earthquake. From those figures it can be seen that structures that collapsed in this earthquake were built over soil deposits with predominant periods of vibration between 1.0 and 2.0s These predominant periods correspond approximately to soft clay deposits with thicknesses between 20 and 45m.



(a) (b)

Figure 2. (a) Soil deposit isoperiods in Mexico City according the 1987 seismic code. (b) Clay deposits isodepths in Mexico City according the 1987 seismic code. Magenta markers indicate collapsed structures during the 2017 Puebla-Morelos earthquake.

The current seismic design code in Mexico City was introduced in 2004 in which several modifications from the 1987 version were made (NTCS-04 2004). One of those modifications corresponds to the subdivision of the 1987 zone III into four subzones. Therefore, the determination of design forces for structures in Mexico City is currently obtained using six different zones. Figure 3 presents the current microzonation of the city along with the markers that indicate the location of the collapsed buildings during the M_w7.1 2017 Puebla-Morelos earthquake. In this case, it is observed that the collapsed structures concentrate in zones IIIa and IIIb of the current code.

As mentioned earlier, soft soil deposit predominant periods in these zones range between 1s and 2s. This soft soil predominant periods, coupled with the frequency content of the relatively short source-to-site distance of the 2017 event, and structural deficiencies that will be mentioned in the next section, are the key factors of the damage observed in structures having between 1 and 10 stories with flexible structural systems.

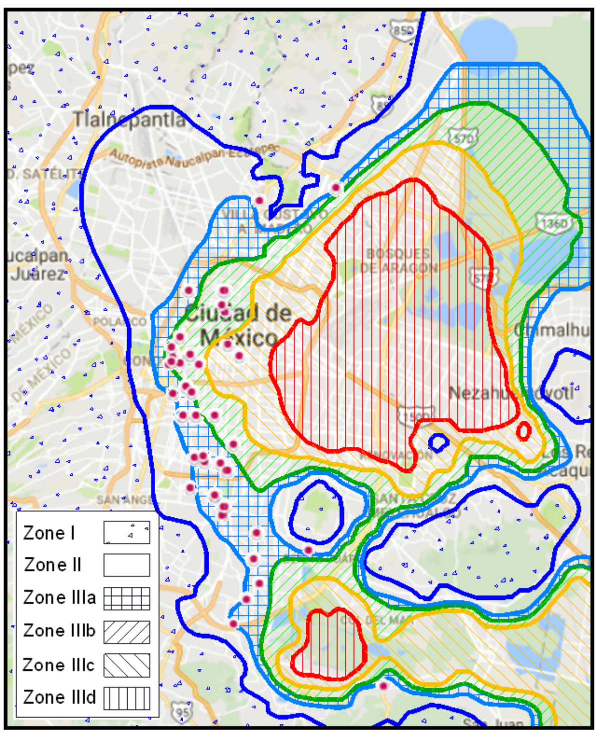


Figure 3. Soil types microzonation according to the Mexico City 2004 seismic design code.

A comparison of seismic design spectra corresponding to two different soil type zones for the 1976, the 1987, and the 2004 Mexico City seismic codes is shown in Figure 4. Figure 4(a) compares design spectra from a site in the 1976 code transition zone, and zone II of the 1987 and 2004 codes. The 1976 code has a plateau with an amplitude of 0.2g starting at 0.5s and ending at a period equal to 2.0s. On the other hand, the amplitude of the two most recent codes is significantly higher and corresponds to 0.32g. The plateau's length of these two codes is fairly similar, starting at a period of around 0.2s and ending at a period around 1.4s. The spectra shown in Figure 4(b) corresponds to a soft soil site according to the 1976 code, a zone III site according to the 1987 code, and a zone IIIb site according to the 2004 version. The design spectrum in the 1976 seismic code had a plateau equal to 0.24g, starting at a period of 0.8s and ending at a period of 3.3s. The amplitude of the plateau for the two most recent codes is equal 0.4g and 0.45g for the 1987 and the 2004 codes, respectively. The plateau recommended by the 1987 version of the code starts at 0.6s and ends at 3.9s while the corresponding periods for the 2004 code starts at 0.85s and ends at 3s.

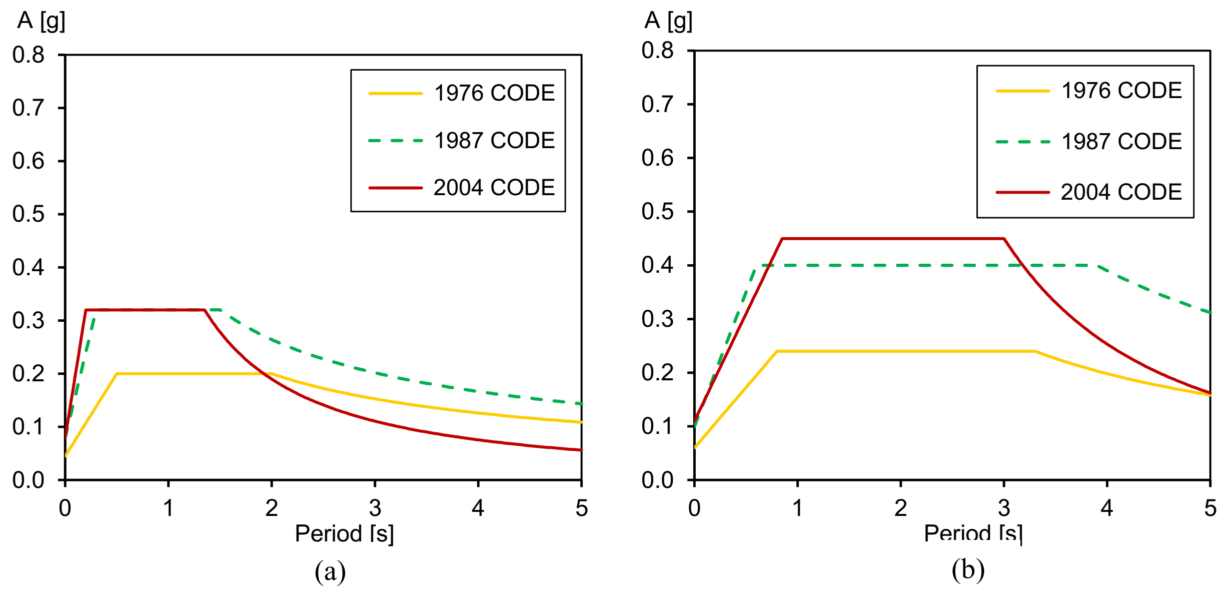


Figure 4. Design spectra for two different soil type zones. (a) Transition zone for the 1976 code and Zone II for the 1987 and 2004 codes. (b) Soft soil zone for the 1976 code, Zone III for the 1987 code and Zone IIIb for the 2004 code.

3. Collapse statistics

The following statistics summarize the information gathered from the reconnaissance mission made by the team of Stanford's John A. Blume Earthquake Engineering Center, and complemented with information from newspapers and social media (Ruiz 2017; López Linares et al. 2017; The Huffpost 2017). The structural characteristics of each building before the earthquake were obtained from visual inspection using Google Street View. The structural system was determined from the study of photographs of each building both prior and after the earthquakes. A total of 46 collapsed structures occurred as a result of the earthquake including 44 buildings, one pedestrian overpass, and one pedestrian bridge located between two buildings. This section summarizes the main characteristics of the 44 collapsed buildings.

Figure 5 presents a histogram of the structural systems of the collapsed buildings. It is worth noticing that the structural system of more than 60% of the 44 collapses corresponds to a reinforced concrete (RC) column and flat slab system. This percentage is even higher than the observed in the 1985 earthquake which corresponded to 43.3% (91/210) (Meli and Miranda, 1985). The flat slab system is a system was developed in the early 1900s as a "beamless" primarily aimed at carrying gravity (vertical) loads and to facilitate construction by simplifying the formwork. However, when used as a lateral resisting system, the system is characterized by a very low lateral stiffness and prone to experiencing punching shear failures and soon after the slab-to-column connection loses it vertical carrying capacity it leads to a partial or total collapse of the building. During the 1985 earthquake 91 buildings with this structural system collapsed. In the emergency code that was issue a few days after the 1985 earthquake design forces for this structural system were greatly increased in order to disincentivize its use, however unfortunately it is still allowed by the code and continues to be used in building constructed after 1985. An example of the total collapse of one of these flat-slab reinforced concrete buildings is shown in Figure 6.

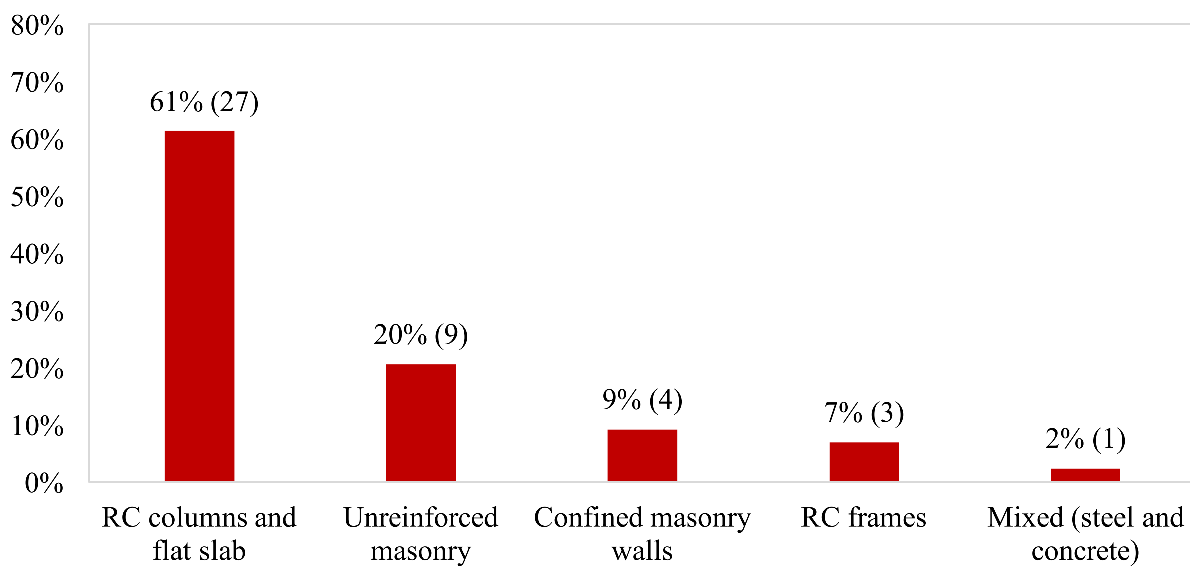


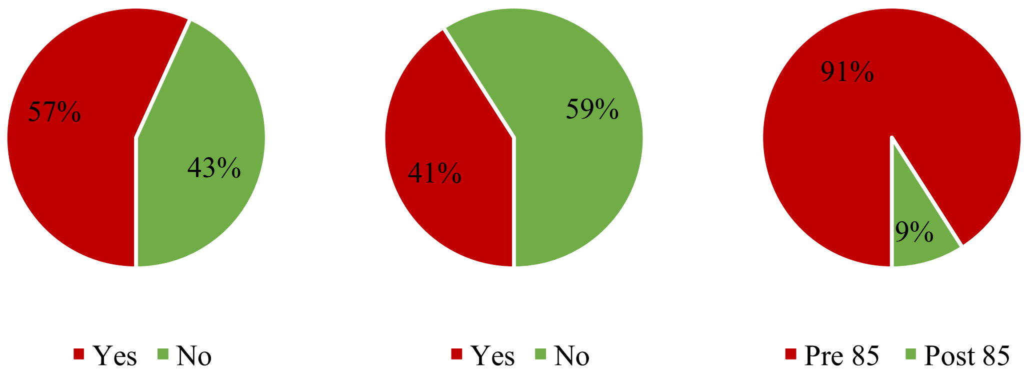
Figure 5. Distribution of structural systems for collapsed buildings in the 2017 earthquake.

(a) (b)

Figure 6. Building with flat slab system at Viaducto Miguel Alemán 106, Piedad Narvarte. (a) Before Sep. 19, 2017 (taken from Google Street View); and (b) After Sep. 19, 2017 (The Huffpost 2017).

The number of collapsed masonry structures—considering unreinforced masonry (URM) and confined masonry walls (CMW) in this structural group—contributed to almost 33% of the total collapses in 2017. In contrast, during the 1985 earthquake, only 13 out of 210 documented collapses (6%) were masonry structures (Meli and Miranda 1985). The proximity of the 2017 produced a larger intensity in the short period spectral region leading to a larger proportion of collapsed buildings with these structural systems.

Figure 7(a) shows that 57% of the collapsed buildings were soft-story structures. A soft story is produced when one story, which is typically the ground level, has a lateral strength and lateral stiffness that it is significantly smaller than the other stories. This structural deficiency is usually produced by the presence of parking garage in the ground level while upper stories have many infill masonry walls making them laterally stronger and stiffer. During an earthquake, lateral deformations concentrate in the soft story which combined with inadequate reinforcing detailing leads to shear failures in the columns. Once shear failures are produced the column typically loses its vertical carrying capacity and a collapse is produced. This structural deficiency could have been the main reason triggering their collapse. An example of the collapse of this type of structure is shown in Figure 8. This failure has been observed in several previous earthquakes. For instance, the 1994 Northridge earthquake evidenced the vulnerability of wooden multistory buildings with a soft first story (Figure 9(a)). Likewise, the Puebla-Morelos earthquake triggered the same type of collapse in flat slab concrete structures with soft stories (Figure 9(b)). Soft stories were identified as the primary reason that lead to the collapse of 8% of the building in the 1985 earthquake (Meli and Miranda 1985) but the percentage of collapsed building with this structural deficiency was now significantly higher.



(a) (b) (c)

Figure 7. (a) Soft story buildings; (b) Corner buildings; and (c) Approximate building age

As mentioned before, the damage progression in building with soft first story often initiates with the failure of one or more columns in the first floor due to the concentration of lateral deformations (interstory drifts) at this level. Unless the reinforced concrete columns have an adequate amount and adequately placed transverse reinforcement (stirrups) to develop ductile flexural plastic hinges, the columns suffer brittle shear failures. An example is shown in figure 10, where practically all of the columns in the ground level of a five-story building had failed in shear and the building was on the verge of collapse.

Figure 7(b) also shows that 59% of the collapsed structures were buildings located at corners of a building block. These buildings often have masonry infills in two sides facing neighboring structures but not on the two sides facing the street, leading to motions with stronger torsional response (rotation of floor systems about a vertical axis). Collapse of buildings located in corners was also a prevalent problem in the 1985 Michoacán earthquake where 42% of collapsed buildings were located on a block corner (Meli and Miranda 1985). It is important to note that ibn this earthquake one fourth of the collapsed structures (11 out of 44) had both structural deficiencies, soft story and located were corner buildings.

Figure 8. Residential building with a soft first story at Balsas 18, Miravalle. (a) Before Sep. 19, 2017 (taken from Google Street View); and (b) After Sep. 19, 2017 (photo by Pablo Heresi).

(a) (b)

Figure 9 (a) Collapsed multistory apartment building with soft first story in the Northridge Earthquake in 1994 (USGS/ D. L. Carver); and (b) Residential building at Tokio 517, Portales Norte after Sep. 19, 2017 (The Huffpost 2017).

With respect to the age of construction, Figure 7(c) shows that approximately 90% of the collapsed buildings were built prior to the 1985 earthquake. This suggests that most structures following post-85 code regulations performed reasonably well, but further study is necessary. On the other hand, it is very concerning that the cause of collapse of many pre-85 buildings was the same as 32 years ago. This suggests a lack of structural evaluation following the 1985 earthquake and/or an inadequate implementation of effective retrofit strategies. Furthermore, the possibility of cumulative damage, in particular lateral stiffness degradation in non-ductile reinforced concrete structures may have played a role in the poor performance of many of these older buildings that collapse and deserves further study.

Figure 10. Shear failures in columns in a RC flat slab building with a soft first story at Paz Montes de Oca 93, Col. Gral Anaya (photos by Pablo Heresi).

According to the gathered data, half of the collapses were total collapses and the remaining half were partial collapses (Figure 11). The latter includes the failure of one or more stories in the bottom of the building and the collapse of one or more intermediate stories. It is important to mention that two of the forty-four reported collapses were most likely induced by the collapse of a neighboring taller building. This is the case of a six-story building (Bretaña 90, Zacahuitzco) that collapsed on top of a two-story house (Bretaña 92, Zacahuitzco), and a two-story house (Escocia 33, San Andrés Park) that was pulled down when its neighboring five-story building collapsed (Escocia 29, San Andrés Park).

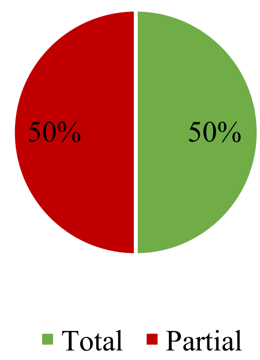


Figure 11. Types of collapse

Figure 12 shows a comparison of the distributions of the number of stories of collapsed structures in the 1985 and 2017 earthquakes. It is evident that the 1985 earthquake had a greater impact on taller structures than the 2017 event. This observation is in agreement with the difference in frequency content from events resulting from the difference in magnitudes and considerably different source-to-site distances. As mentioned before, closer events, such as the 2017 earthquake, have more high-frequency content and therefore are expected to have a higher impact on shorter period structures than those that were affected during the large magnitude distant 1985 earthquake.

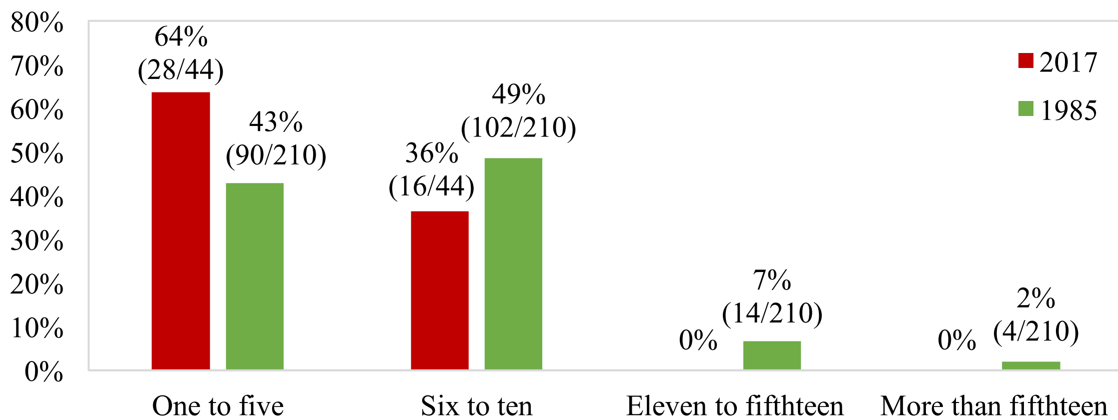
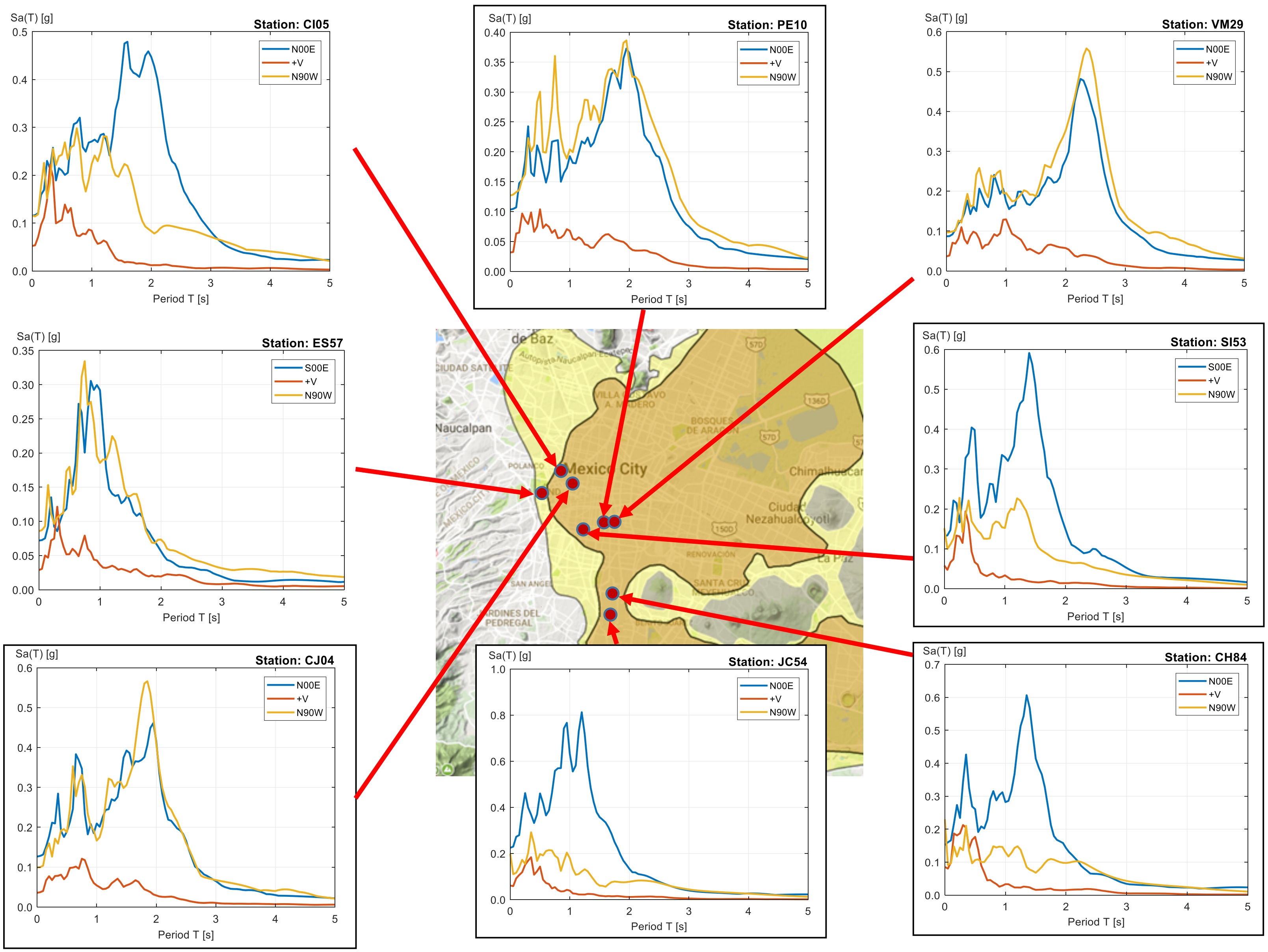


Figure 12. Distribution of the number of stories of the collapsed buildings for the 1985 and the 2017 Earthquakes



Map and ground motion records kindly provided to us by CIRES

4. Summary and Conclusions

On September 19th, 2017, exactly on the anniversary of the great 1985 Michoacán earthquake, an intermediate-depth fault-normal earthquake occurred approximately 120 km (75 miles) from Mexico City. The earthquake produced ground motions in Mexico City with peak ground accelerations of approximately 0.05g on firm soil and of 0.2g on soft soil. The earthquake produced the collapse of 46 structures and 219 fatalities in Mexico City.

Faculty and PhD students of the John A. Blume Earthquake Engineering Center travelled to Mexico City on the same day of the earthquake to document the performance of structures. From their reconnaissance and data gathered a preliminary evaluation of the characteristics of the 44 buildings that collapsed has been presented. The large majority of the buildings that collapsed had one or more of the following characteristics: (1) being older pre-1985 non-ductile reinforced concrete structures; (2) having a structural lateral resisting system consisting of flat-slabs supported by reinforced concrete columns; and (3) having a soft story. Also very common (in 41% of the collapsed buildings) were buildings located in block corners where effects of torsion are typically more severe.

All of these characteristics were also commonly observed during the 1985 earthquake. This highlights that, probably, inadequate attention was given to the seismic evaluation of existing structures with these characteristics after the 1985 earthquake to evaluate if a seismic retrofit was necessary or not. Perhaps some of the collapses and loss of life that occurred in this earthquake could have been prevented. After the 1985 earthquake an emergency code obligated owners of buildings that suffered structural damage to report this damage to city officials but, to the best of our knowledge, there was no obligation to evaluate buildings with no damage or only with nonstructural damage. A notable exception were public schools that most of them were seismically evaluated after the 1985 earthquake and many of them were seismically upgraded leading, in the large majority of cases, to a good performance in this earthquake. Unfortunately, the Enrique Rebsamen school that collapsed and resulted in the deaths of 32 children and 5 adults was a relatively small private school that appears that was not only not subjected to the same evaluation/retrofit process, but had several modifications done in recent years including the addition of one level in one of the two buildings that collapsed in the school.

Non-ductile reinforced concrete structures and/or those with soft stories have also produced many collapsed structures in other countries such as the United States. However, these problems are exacerbated in Mexico City by a higher seismicity and by very soft soil deposits that greatly amplify the intensity of ground motions.

A number of investigations are underway to determine if changes are necessary to the new Mexico City building code that was about to be published. Preliminary evaluations of the ground motions records available to date indicate that response spectral ordinates did not exceeded those of appendix A of the 2004 code (Ordaz et al 2003) or those of the new code that was about to be published. Similarly, preliminary evaluation of some of the post-1985 structures that collapsed suggest that these structures did not comply with one or more of the requirements of the building code.

Perhaps one of the most important lessons from this earthquake is the need to devote more attention to existing structures and in particular to issuing a possible mandate that would provide a time frame in which owners of pre-1985 structures with certain characteristics and located in the former lake bed of Mexico City would have the obligation to have their structures seismically evaluated by a structural engineer. In California, several of these ordinates have successfully been implemented such as the 1986 Unreinforced Masonry (URM) Buildings law that in many jurisdictions requires a mitigation program of these type of structures, or the 1953 State Bill that required all hospital in the State to be seismically evaluated in order to meet seismic safety goals by classifying them by level of danger of collapse and setting deadlines for retrofitting and/or reconstruction. Other more recent examples of mandates to evaluate existing buildings prone to experience collapse in the event of strong earthquake are the non-ductile reinforced concrete ordinance recently passed in the City of Los Angeles or the soft story ordinance recently passed in the City of San Francisco requiring owners to have their structures evaluated by structural engineers and to seismically upgrade them if found necessary.

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