



# Observations about the seismic response of RC buildings in Mexico City

© The Author(s) 2020

**Sergio Alcocer, M.EERI<sup>1</sup>, Anahid Behrouzi, M.EERI<sup>2</sup>, Sergio Brena, M.EERI<sup>3</sup> , Kenneth J Elwood, M.EERI<sup>4</sup>, Ayhan Irfanoglu, M.EERI<sup>5</sup>, Michael Kreger, M.EERI<sup>6</sup>, Rémy Lequesne, M.EERI<sup>7</sup>, Gilberto Mosqueda, M.EERI<sup>8</sup>, Santiago Pujol, M.EERI<sup>5</sup> , Aishwarya Puranam, M.EERI<sup>9</sup>, Mario Rodriguez, M.EERI<sup>10</sup>, Prateek Shah<sup>5</sup>, Andreas Stavridis<sup>11</sup>, and Richard Wood<sup>12</sup>**

## Abstract

Over 2000 buildings were surveyed by members of the Colegio de Ingenieros (CICM) and Sociedad Mexicana de Ingenieria Estructural (SMIE) in Mexico City following the Puebla-Morelos Earthquake of 2017. This inventory of surveyed buildings included nearly 40 collapses and over 600 buildings deemed to have structural damage. Correlation of damage with peak ground acceleration (PGA), peak ground velocity (PGV), predominant spectral period, building location, and building properties including height, estimated stiffness, and presence of walls or retrofits was investigated for the surveyed buildings. The evidence available suggests that (1) ground motion intensity (PGV) drove the occurrence of damage and (2) buildings with more infill and stiff retrofit systems did better than other buildings.

---

<sup>1</sup>The University of Texas at San Antonio, San Antonio, TX, USA

<sup>2</sup>Cal Poly San Luis Obispo, San Luis Obispo, CA, USA

<sup>3</sup>University of Massachusetts Amherst, Amherst, MA, USA

<sup>4</sup>The University of Auckland, Auckland, New Zealand

<sup>5</sup>Purdue University, West Lafayette, IN, USA

<sup>6</sup>The University of Alabama, Tuscaloosa, AL, USA

<sup>7</sup>The University of Kansas, Lawrence, KS, USA

<sup>8</sup>University of California, San Diego, La Jolla, CA, USA

<sup>9</sup>National Taiwan University, Taipei, Taiwan

<sup>10</sup>Universidad Nacional Autónoma de México, Mexico City, Mexico

<sup>11</sup>University at Buffalo, Buffalo, NY, USA

<sup>12</sup>University of Nebraska–Lincoln, Lincoln, NE, USA

## Corresponding author:

Aishwarya Puranam, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 106.  
Email: ashpuranam@gmail.com

---

## Keywords

Reinforced concrete, earthquake damage, 2017 Puebla-Morelos Earthquake, structural damage, seismic response

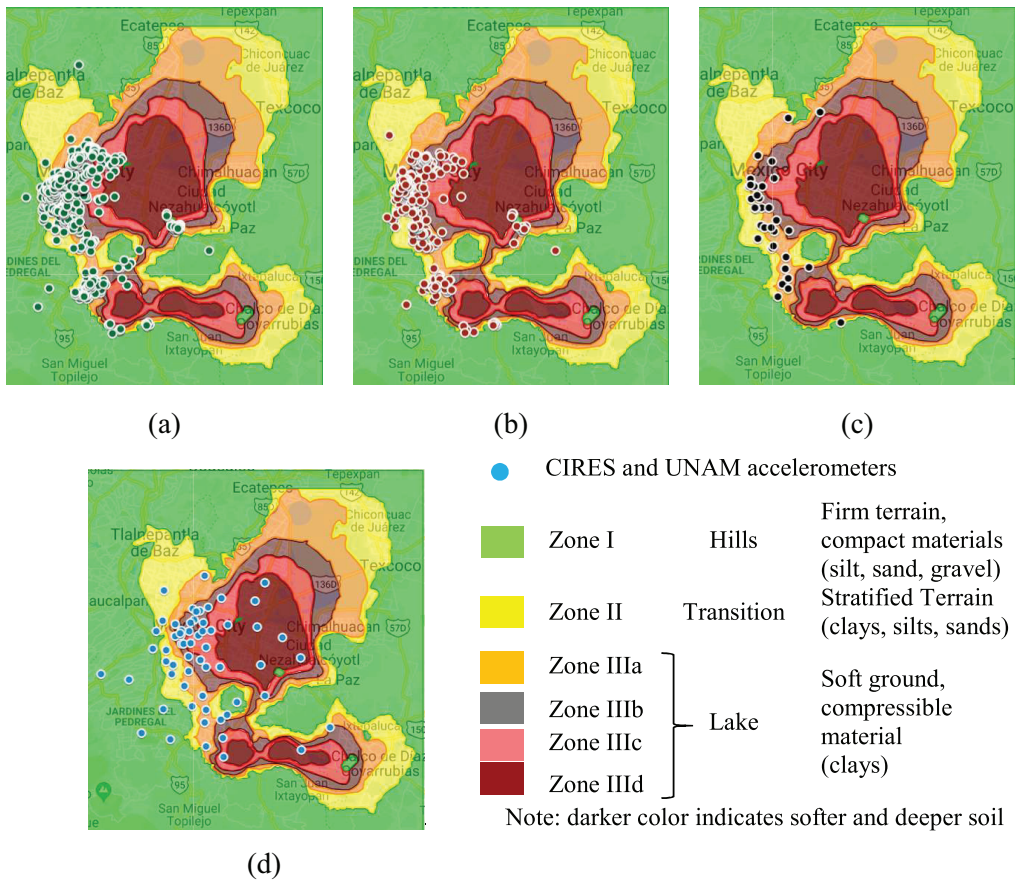
Date received: 3 June 2020; accepted: 4 June 2020

## Introduction

The Puebla-Morelos (or Central Mexico) Earthquake occurred on 19 September 2017 and had a moment magnitude of 7.1 (SSN, 2017; USGS, 2017). The Colegio de Ingenieros Civiles de Mexico (CICM) and Sociedad Mexicana de Ingenieria Estructural (SMIE) organized a survey following the earthquake to assess damage and to collect information and identify buildings that posed a risk to occupants requiring evacuation. Approximately 35 teams visited the most affected areas of the city and surveyed nearly 2000 buildings (CICM and SMIE, 2017a,b). The teams were composed of civil engineers and civil engineering students and each team was led by an experienced structural engineer. Teams were assigned sections of the city to survey and members walked throughout their assigned sections and randomly selected structures to be surveyed. Engineers attempted to enter each structure to survey the interior of the building. Observations of damage were noted on a standardized form. Information collected by the survey teams was sent back to CICM where it was collected and organized into a spreadsheet along with photographs. Well-trained structural engineers along with experienced researchers from local universities carefully reviewed the field data to identify and flag errors related to damage classification. Teams were sent back to the field to correct errors. The engineers also collected (1) information about geotechnical zoning in the city with help from the Sociedad Mexicana de Ingenieria Geotecnica (SMIG) and (2) ground motion records from 61 stations across the city made available by the Centro de Instrumentacion y Registro Sismico C.A. (CIRES) and National Autonomous University of Mexico (UNAM). Locations of surveyed buildings and stations for recording ground motions are shown in Figure 1 superimposed on geotechnical zones.

Data collected and shared by CICM and SMIE included building properties such as location, number of stories, and use, as well as the type of damage observed at each location. The data indicate for each surveyed structure whether team members observed collapse, partial collapse, damage to structural elements (beams, columns, or walls), damage to non-structural elements, inclination, or differential settlement. Throughout this article, the term “collapse” is used to refer to the complete loss of elevation of one or more stories (Figure 2). All structures identified by CICM and SMIE (2017) as having collapsed were verified by the writers in person during subsequent surveys or via news reports. Structures identified by CICM and SMIE as exhibiting partial collapse were omitted from this study because the definition was less clear. In relation to the survey done by CICM and SMIE, the term “damage” is used herein to refer to instances of “structural damage” where one or more structural elements exhibited clear signs of distress caused by shear, bond, or axial stresses (Figure 3). Buildings with damage to only non-structural elements are not included among damaged buildings considered in this article.

A team of researchers from universities in the United States, Mexico, and New Zealand (the writers) subsequently surveyed approximately 110 buildings and instrumented 13 buildings to measure fundamental period. All data collected are available at <https://data-centerhub.org/resources/14746>. These additional surveys provided detailed data regarding



**Figure 1.** Locations of buildings surveyed by CICM and SMIE and CIRES accelerometers superimposed on maps of geotechnical zones (CICM and SMIE, 2017): (a) buildings without structural damage, (b) buildings with structural damage, (c) collapsed buildings, and (d) accelerometer locations.



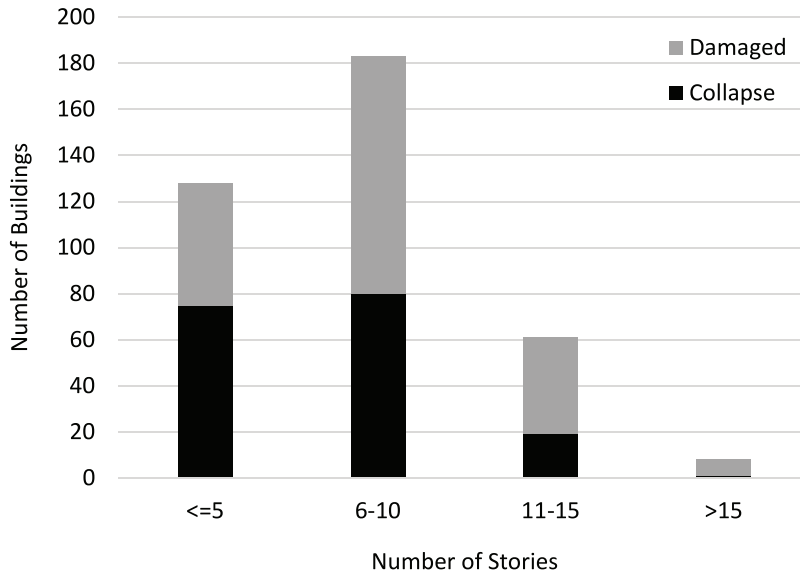
**Figure 2.** Examples of collapses in buildings surveyed by CICM and SMIE (2017). Other examples are available here: <https://notas.tuhogarmexico.com/2017/09/28/asi-lucian-asi-lucen-ahora-los-edificios-se-derrumbaron-en-la-cdmx/>



**Figure 3.** Examples of structural damage in buildings surveyed by CICM and SMIE (2017).

the type and extent of damage observed. Each structure was assigned a damage index that ranged from 1 for little or no structural damage to 10 for structures with partial or complete collapse or failure of structural members. This survey also recorded information about the structural systems, including the presence of retrofits and the cross-sectional area and orientation of reinforced concrete columns and walls as well as masonry infill walls. Buildings were selected following these criteria: (1) location (buildings were surveyed in the areas illustrated in Figure 1 with preference for areas where damage indicated higher intensity), (2) inclusion of both buildings with and without damage in areas investigated, and (3) accessibility and disruption of use. Most undamaged buildings included in this survey were located near surveyed damaged buildings and appeared to be similar in proportions and vintage to surveyed damaged buildings.

This article reflects on some of the observations made after the 1985 Michoacan Earthquake and uses data available from 2017 to investigate the correlation of structural damage and collapse with building properties, ground motion intensity, and geotechnical conditions. The list of building properties studied is provided in Appendices 1 and 2. Appendix 1 refers to properties collected and studied by the writers. They follow (in format and content) from previous investigations by Shiga et al. (1968), Riddell et al. (1987), Hassan and Sozen (1997), Donmez and Pujol (2005), O'Brien et al. (2011), Islam et al. (2018), and Pujol et al. (2020). Appendix 2 lists information collected by CICM that is described at <https://www.sismosmexico.org/informes>. Considered ground motion characteristics included peak ground acceleration (PGA), peak ground velocity (PGV), and the predominant ground motion period, defined as the period associated with the maximum spectral response for a linear system that may be affected by the properties of the site. Geotechnical conditions were considered qualitatively by correlating the locations of damaged buildings with geotechnical zones.



**Figure 4.** Reinforced concrete buildings with severe structural damage and partial or complete collapse, Mexico City, 1985 (Reproduced using data from Aguilar et al., 1989).

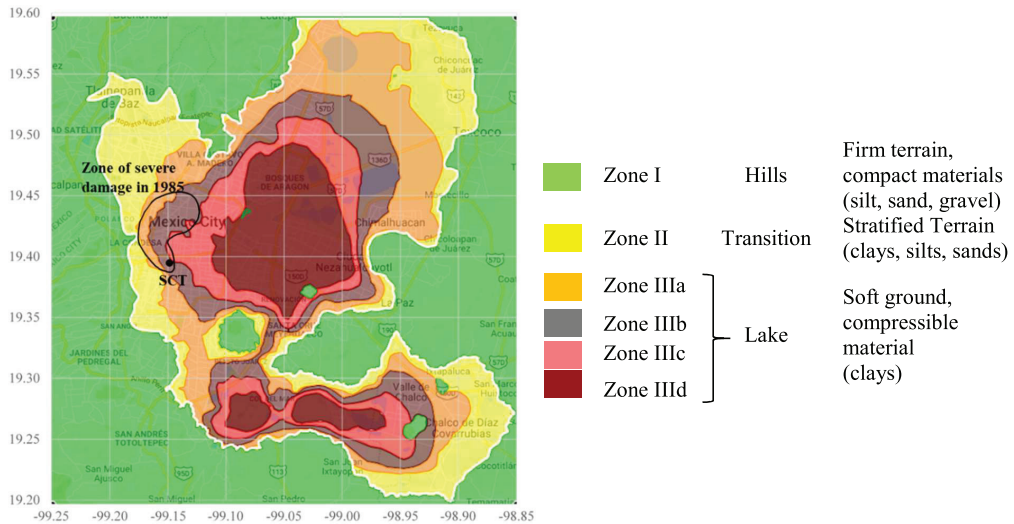
## Analysis

### *Background: 19 September 1985 Michoacán Earthquake (M 8.1, USGS, 1985)*

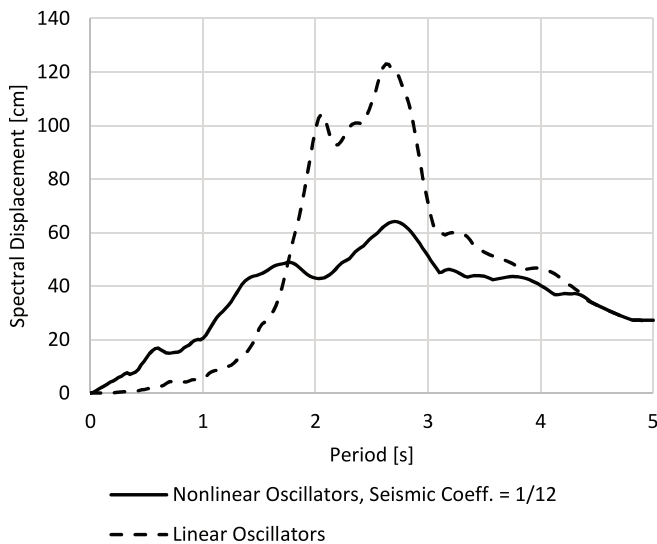
In the 1985 Michoacan Earthquake, the majority of collapses in Mexico City occurred for buildings with 6–10 stories (Figure 4), although the majority of the buildings in the city had 5 or fewer stories (Aguilar et al., 1989). Detailed information about this set of buildings was summarized by Aguilar et al. (1989) and these data have been used by a number of researchers to study the response of buildings to the 1985 Michoacan Earthquake (Aguilar et al., 1989; NZSEE, 1985; Stone et al., 1987; Teran-Gilmore and Bertero, 1992).

Only a limited number of ground motions were recorded within the city during the 1985 event. The record from Station SCT (located halfway between rock and the deepest soil deposits on the west side of the city, Figure 5a) produced the linear-elastic and nonlinear (elastic-plastic) displacement spectra for single-degree-of-freedom (SDOF) oscillators shown in Figure 5b. The linear-elastic displacement spectrum has large amplifications between 1.5 and 3.5 s. The consensus of the profession seemed to be that the large amplifications in this range explained the relatively large number of damaged and collapsed buildings with 6–10 stories. The stiffness of the soils, distance from the source, focal mechanism, and magnitude of the earthquake have been suspected to have produced this concentration of demand and damage in taller buildings (Aguilar et al., 1989; NZSEE, 1985; Stone et al., 1987).

An issue that may have received less attention is that spectra with narrow bands of large amplification do not affect nonlinear systems the same way they affect linear systems (Pujol et al., 2018). Large amplifications in narrow period ranges resemble the phenomenon of resonance. Nonlinear structures are not prone to resonance because their stiffness changes from one instant to the next during strong ground motion. Most of the structures affected by the earthquake of 1985, however, were flexible and brittle structures with



(a)



(b)

Note:

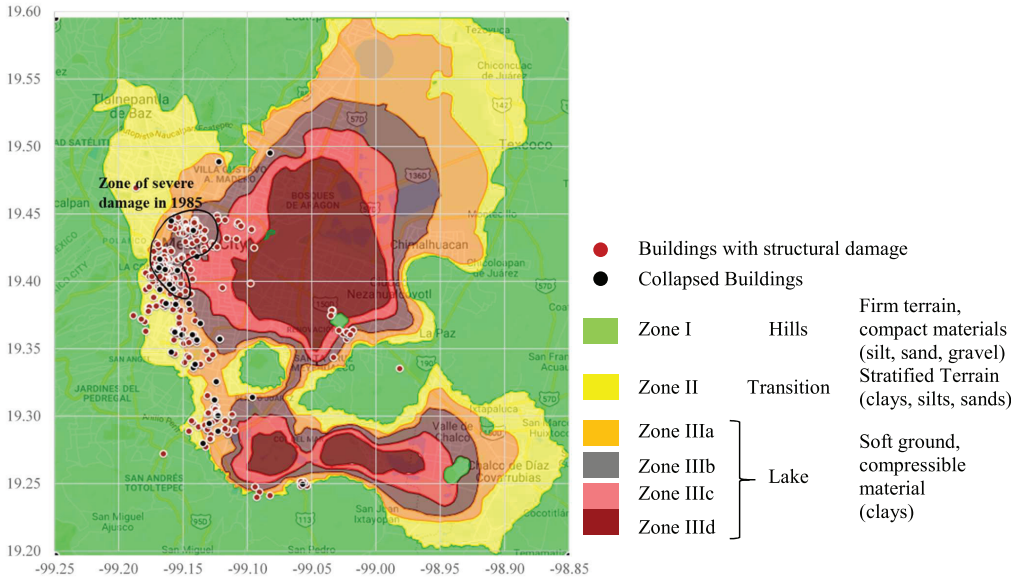
‘Linear oscillator’ refers to a linear-elastic SDOF spring-mass system which remains in its linear range of response and has a damping ratio of 5%.

Non-linear oscillator, seismic coefficient = 1/12 refers to nonlinear SDOFs with a base shear coefficient (ratio of base shear strength to building weight) of 1/12.

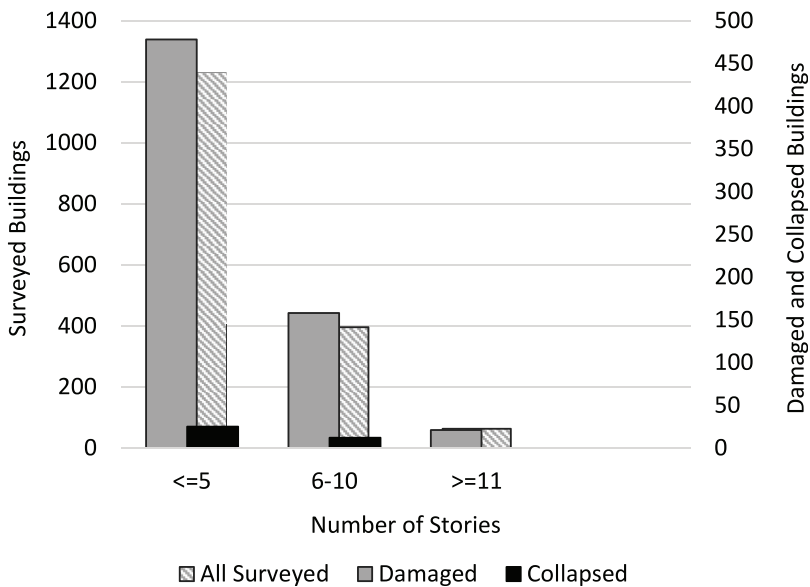
**Figure 5.** (a) Location of station SCT and zone of severe damage in 1985 (using data from Stone et al., 1987) and (b) displacement spectra for SDOF linear and nonlinear oscillators to the E-W component of the 1985 earthquake recorded at the SCT station (damping ratio = 5%).

limited ability to retain their structural integrity during displacement cycles applied after they reached their lateral strength. It seems reasonable to believe that, after initial softening caused by cracking, their response depended on the magnitude of linear demands at elongated periods and increased damping. In that scenario, the range of periods with large amplifications in linear structures would be critical in the retrofit or evaluation of such brittle structures. Nevertheless, this range is likely to be less critical for ductile nonlinear structures.





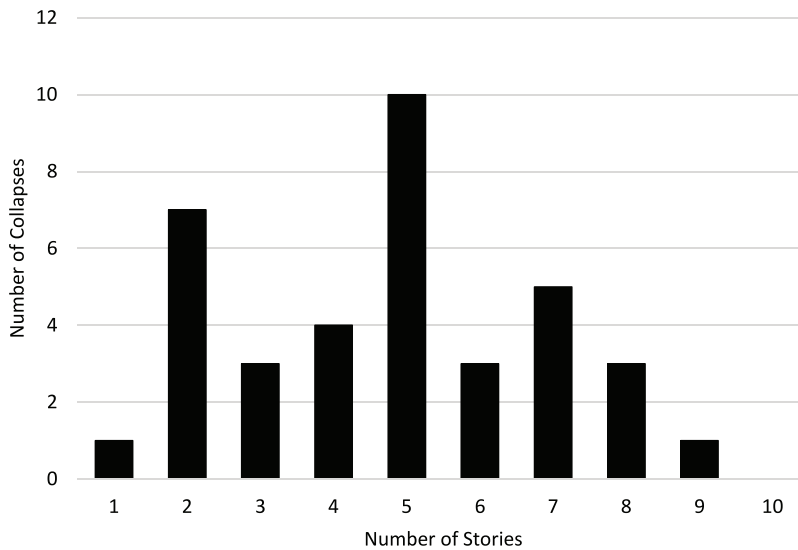
**Figure 6.** Locations of damaged and collapsed buildings after 2017 Puebla-Morelos Earthquake.



**Figure 7.** Buildings surveyed after 2017 Puebla-Morelos Earthquake (data from CICM and SMIE, 2017)—note the use of two different vertical scales.

**2017: 19 September Puebla-Morelos Earthquake (M 7.1, USGS, 2017)**

Buildings surveyed by CICM and SMIE after the 2017 Puebla-Morelos Earthquake are located and classified in Figures 6 and 7. It is interesting that relative to the observations from 1985, in 2017 (1) the reported structural damage seems to have shifted toward shorter

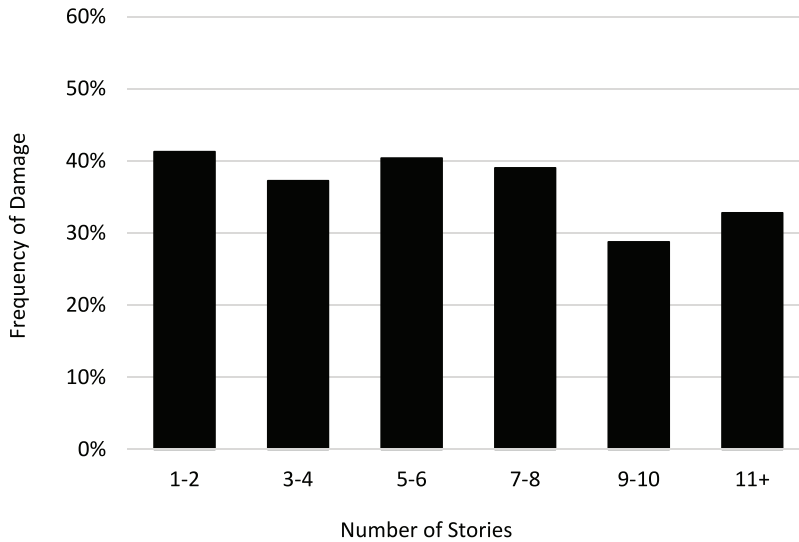


**Figure 8.** Height, in terms of number of stories, of collapsed buildings in Mexico City, 2017 Puebla-Morelos Earthquake.

buildings, (2) more buildings were reported damaged, and (3) fewer collapses occurred. Figure 7 illustrates that the correlation between damage and building height was not clear in 2017. In general, the distribution of damage is shifted toward buildings with 5 or fewer stories, which, by inspection, is the most prevalent class of buildings in Mexico City. The distribution of damage therefore reflected to some extent the distribution of buildings in the city. The CICM-SMIE survey reported nearly 40 collapses in the 19 September 2017 Earthquake. Although 10 of these collapses occurred in buildings with 5 stories, the concentration of collapse occurrence in buildings within a given height range (Figure 8) was not as clear as in 1985 (Figure 4).

*Frequency of damage versus building height.* Correlation between damage and building height was also investigated by estimating frequency of damage for different ranges of building heights. Frequency of damage is defined as the number of buildings classified as having structural damage or collapse divided by the number of buildings inspected (as opposed to total number of buildings) for each range of building height. This definition was used because the writers do not have an accurate count of buildings in Mexico City and because it would not make sense to mix in buildings from areas where shaking had low intensity. Note that this definition of frequency results in values much larger than the actual frequency of damage in the entire city because the number of inspected buildings (the denominator) is much smaller than the total number of buildings in Mexico City. In the results from the CICM-SMIE survey, the frequency of damage seems to have been uniform across a wide range of building heights below 15 stories (Figure 9), that is, no concentration of damage is seen for any particular range of building height. The same is true even if one ignores 1- and 2-story buildings (Figure 9), which are often confined masonry structures in Mexico City, while taller buildings tend to be RC frames with masonry infill. While it is not known how survey methods may have influenced the calculated frequency of damage, it is clear that many buildings with fewer than 6 stories ( $N < 6$ ) were damaged (Figure 7).





**Figure 9.** Frequency of damage versus number of stories in 2017.

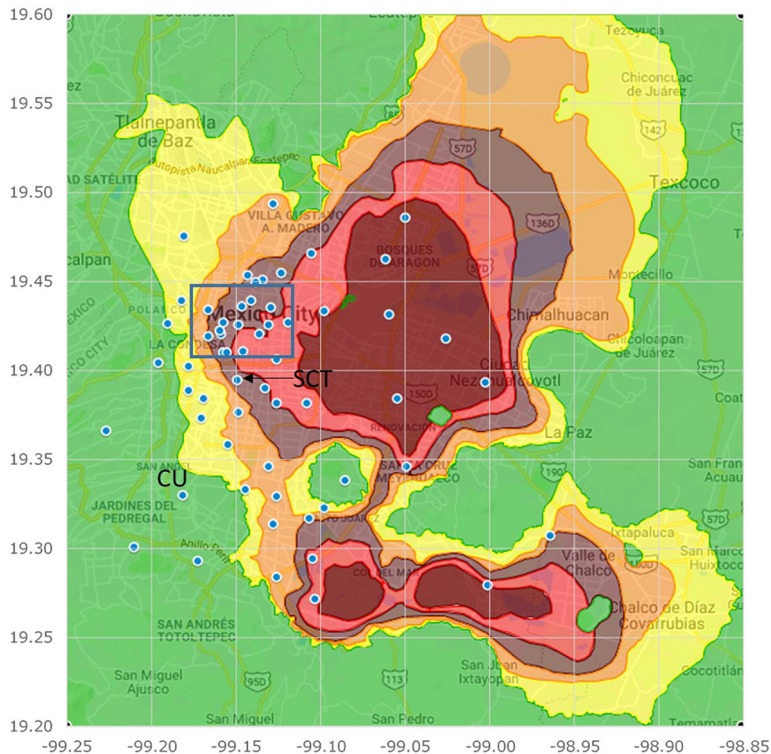
Nevertheless, engineers interviewed by the writers suggested that most of the damaged buildings had 6–8 stories which was a new occurrence of “resonance” similar to that reported in 1985 (a view that dominates design in Mexico City). This interpretation is inconsistent with the data plotted in Figure 9.

*Frequency content of ground motion.* A network of accelerometers maintained by CIRES and UNAM produced 61 records from Mexico City during the 19 September 2017 Earthquake. Figure 10 shows the locations of these accelerometers.

The damage distribution observed in 2017, which in relative terms included more buildings with fewer than 6 stories, could also be interpreted as the result of larger demands at shorter periods (higher frequencies) in relation to the ground motions in 1985. That was indeed the case at station Ciudad Universitaria (CU), located on rock, and for periods shorter than 0.5 s (or frequencies exceeding 2 Hz) (Figure 11a). Nevertheless, in that area, intensity was relatively small and damage was not frequent. In contrast, the ground motions recorded on soil both at station SCT and in the area where most damage occurred (Condesa and Roma districts) show that demands in 2017 were not always higher for shorter periods (higher frequencies) (Figure 11b and c). The records show linear spectral accelerations and displacements for periods of up to 1.75 s were similar in 1985 and 2017. On the other hand, demands for longer periods (lower frequencies) were much smaller in 2017. That observation is consistent with the relative reduction in damage to taller structures.

But how can one then explain the damage in shorter structures that had already survived the motion of 1985 which was at least as demanding as the 2017 motion? Many factors may be at play here. One may be accumulation of damage. Another factor may be that the building inventory aged and may have been altered by remodeling. But other factors are as follows:

1. The variability of ground motion intensity across the city. There were locations in which nearly no signs of intense ground motion were observed with occupants



**Figure 10.** Locations of CIRES and UNAM accelerometers in Mexico City (2017).

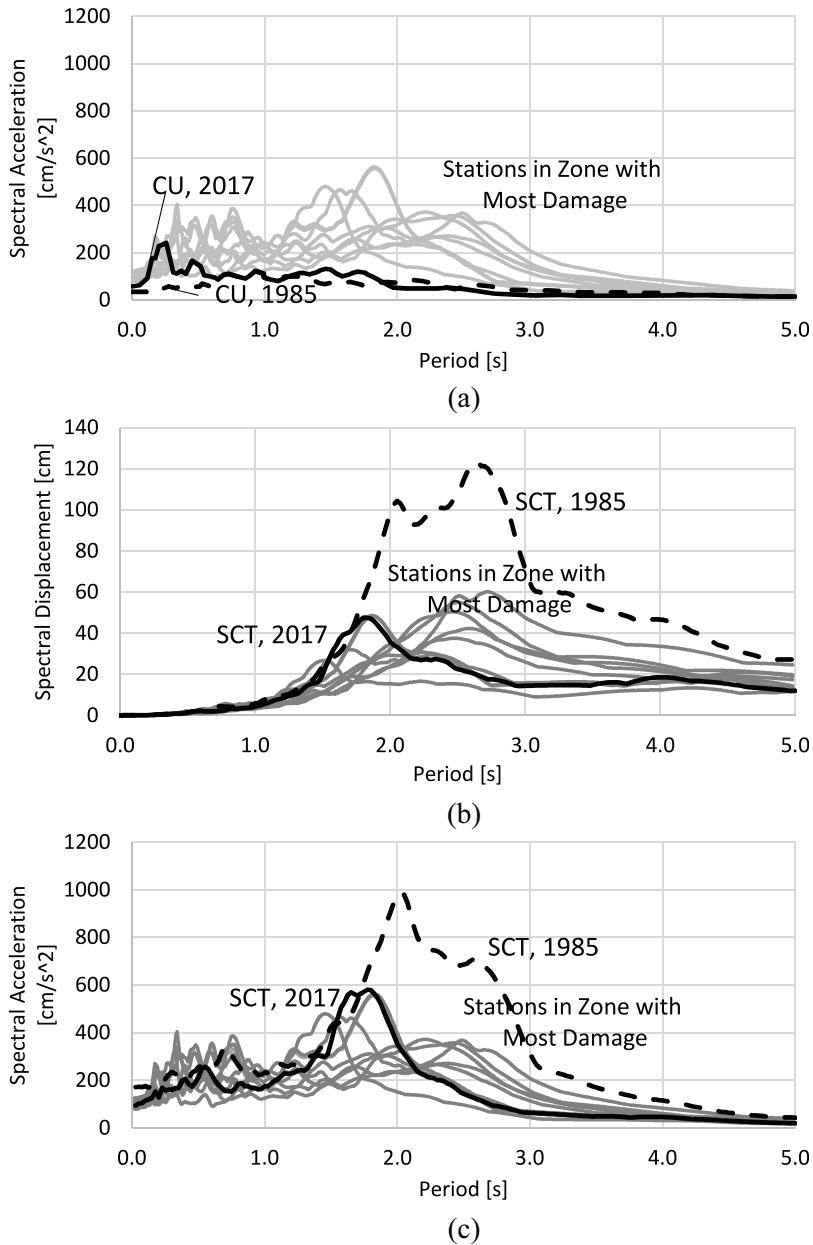
reporting no damage to contents whatsoever. Nevertheless, just a few blocks away, numerous collapses occurred. Unfortunately, accelerometers were too sparsely distributed to provide a comprehensive record of how ground motion intensity varied from block to block (admittedly a difficult task), and how the distribution differed from the 1985 earthquake.

2. The brittleness of the structures. In a brittle and flexible structure, a small change in demand may lead to a large change in response. Flexibility here refers to the inverse of stiffness and not to deformability.
3. All of the mentioned factors combined.

Another interesting question is why the 2017 motion was weaker for long periods (i.e. low frequencies)? There is no clear answer, but factors to be considered include the following:

1. Difference between attenuation of long-period and short-period waves;
2. Whether soils have changed over time because of drainage.

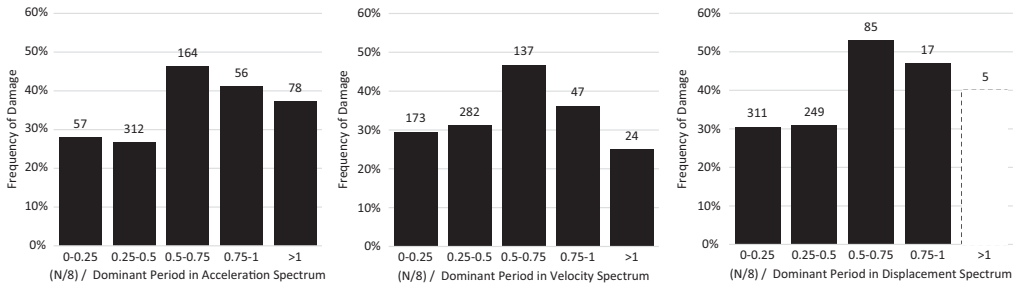
**Geotechnical zones (dominant spectral period) and building period.** The experience of 1985 created a lasting impression among engineers in Mexico and also led to a change in seismic zonation in the City (Iglesias, 1989). Conversations with design professionals in Mexico City indicated that their designs are often aimed at avoiding “resonance.” In 2017, most



**Figure 11.** Spectral displacements and accelerations for the 1985 and 2017 ground motion records (damping ratio = 5%): (a) Station at Ciudad Universitaria (CU), spectral accelerations; (b) Station SCT, spectral displacements; and (c) Station SCT, spectral accelerations.

Note: Gray lines represent stations in zone with most damage.

damage occurred in a narrow geographic “band” running N-S that encompasses three geotechnical (or seismic) “zones” II, IIIa, and IIIb between rock and the old lakebed as illustrated in Figure 6. Most collapses (black dots in Figure 6) occurred in a zone classified according to its soil as “Zone IIIa” (in orange).

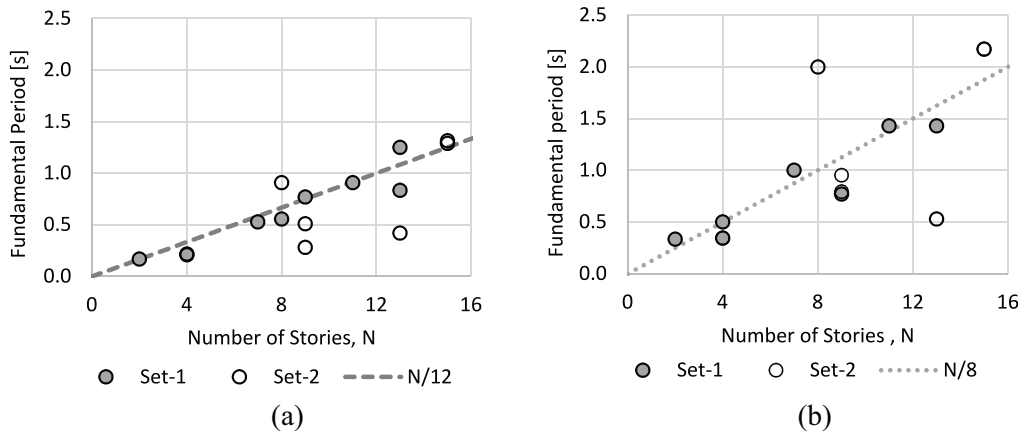


**Figure 12.** Correlation between frequency of damage and dominant spectral period obtained from linear acceleration (left), velocity (center), and displacement (right) spectra.  
 Note: bar labels represent numbers of buildings included in each bin; bins including 10 or fewer buildings are expected to be less representative and are therefore shown with white fill and dashed outline; the plots exclude buildings with  $N < 2$  and those close to stations that recorded  $PGV < 10$  cm/s.

Given the precedent from 1985, the question now is whether the damage and collapses occurred in Zones II, IIIa, and IIIb because the periods of the soils matched the periods of the affected buildings. To address this question, linear response spectra were produced from the acceleration records at station locations shown in Figure 10. From these spectra, the period producing the highest linear response was obtained and named “dominant spectral period.” If the problem of earthquake demand in Mexico City is one of resonance, then one should expect the ratio of building period to dominant spectral period to help organize observations related to instances of damage.

The plots in Figure 12 are attempts to evaluate the idea that resonance explains which buildings experienced more damage in Mexico City during the earthquake of 2017. The vertical axis is percent of surveyed buildings classified as having structural damage and as in Figure 9, this represents frequency of damage for the collected sample of data and not the actual frequency of damage for the entire city. The horizontal axis is the ratio of estimated building period (taken as number of stories ( $N$ )/8) to dominant spectral period from the record closest to that building. Stark (1988) reported periods ( $T$ ) larger than  $N/8$  for reinforced concrete structures from measurements made after the 1985 earthquake in Mexico City. Here,  $N/8$  is assumed to be a reasonable estimate of fundamental period of common RC frames in Mexico City and this assumption is supported by data described in the next section. This assumption was also made considering that in Mexico City masonry infills stiffen buildings producing shorter periods but often in a single direction of the floor plan as discussed later.

Figure 12 suggests that the analogy of resonance was not as useful in 2017 as it may have been in 1985. The buildings most affected by the Earthquake in 1985, considering the peaks in Figures 4 and 11b and c, would correspond to the second and third bins (from the left) in Figure 12a and the second bin in Figure 12 c. But one aspect is clear in this trend: stiffer buildings founded on softer soils (represented by the 0–0.5 range on the chart) had less damage. That is evident also from the absence of damage in the eastern parts of the city, in the old lake area with deeper and longer period soil deposits, where most structures are 1- and 2-story confined masonry houses. These structures were spared as were most stiff buildings in the center of the Kathmandu during the 2015 Gorkha Earthquake in Nepal (Shah et al., 2017).



**Figure 13.** Longest periods of vibration inferred from ambient vibrations: (a) strong (perpendicular) direction and (b) weak (street) direction.

*Instrumenting structures to estimate period.* To test the idea that period is close to  $N/8$  for a typical RC frame in Mexico City (with 3–15 stories), the writers instrumented a number of structures in early 2018 to collect ambient vibration data with the following understanding:

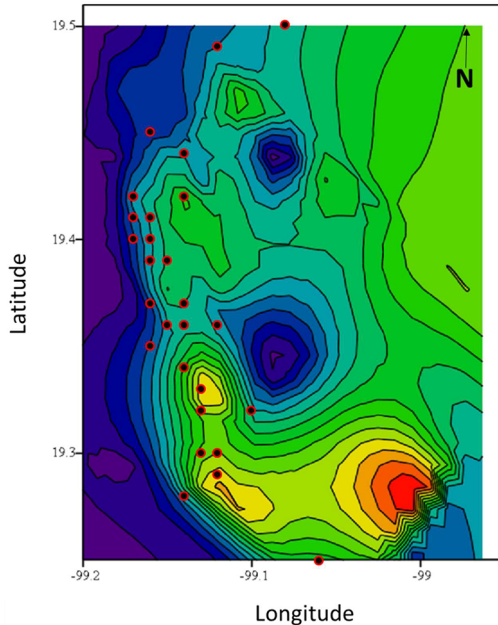
1. Period is sensitive to amplitude of oscillations.
2. Buildings instrumented were likely to have been stiffer before the earthquakes that affected them.
3. We were unlikely to obtain a truly representative sample without investing large resources.
4. Interaction with adjacent structures and soils makes the process difficult.
5. Period identification is not always unequivocal.

With these shortcomings in mind, we identified the longest periods of vibration for each floor plan direction in 13 buildings having RC frames with masonry infills.

The data in Figure 13 were obtained with two separate sets of instruments (represented with filled and open circles), and different data processing methods to identify periods. The spread of the data and differences between systems/processes show that the use of ambient vibrations to estimate the period for the selected buildings was far from crisp. Yet, two trends seem consistent:

1. Except for corner buildings, in the direction perpendicular to the street, buildings had long and continuous infill walls (often made with brick) that provided substantial stiffness. In this direction, the period was approximately  $N/12$  after the earthquake.
2. In the direction of the street, buildings had few and mostly discontinuous and perforated infill walls that did not provide as much additional stiffness to RC frames. In this direction, the period was approximately  $N/8$  after the earthquake.

It follows that assuming the period as being close to  $N/8$  or shorter in the weak direction (that of the street) is reasonable. It also follows that the corner buildings are more vulnerable to drift and prone to torsion, making for compounded vulnerability. Indeed, as pointed out in the report by CICM and SMIE (2017), approximately 50% of collapses



**Figure 14.** Contour of PGV (purple represents low PGV (~10 cm/s) and red represents high PGV (~50 cm/s), and black dots represent collapsed buildings).

occurred in corner buildings, and by inspection the percent of corner buildings in the city building stock is much lower than 50%.

*Ground motion intensity.* The resonance analogy may not apply in the case of 2017 simply because ground motion intensity seems to have had sharp variations within the city. Observations from the field made this evident: as mentioned, some areas of the city had heavy damage while other areas with buildings of similar vintage and height did not. The implication is that the occurrence of damage was not solely a function of period and soil type and may also have been influenced by basin or other plausible effects.

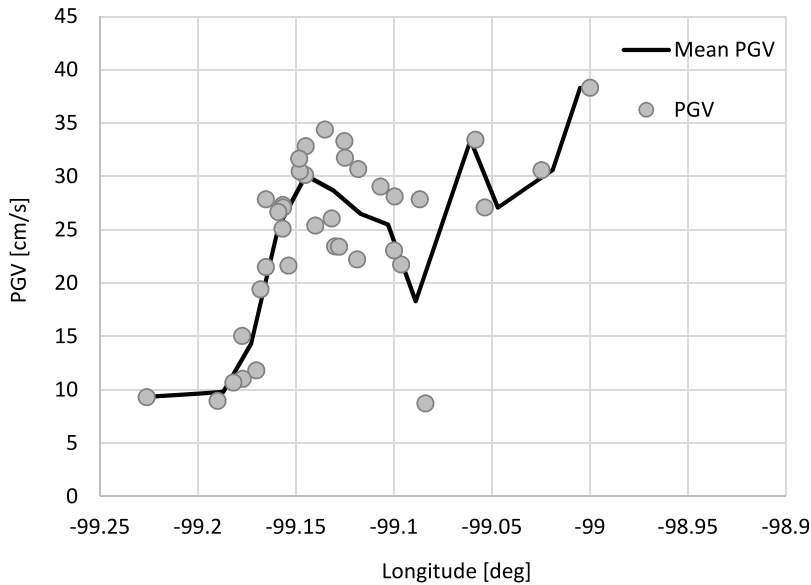
To try to understand better the distribution of damage, a contour map of ground motion intensity (Figure 14) was produced using values of PGV obtained from acceleration records published by CIRES.<sup>1</sup> PGV has been reported to correlate well with drift demand (Laughery, 2016; Sozen, 2003).

The contour map includes dots representing locations of building collapses. At first glance, it appears as if collapse locations match locations with higher values of PGV. But a closer look reveals that a number of collapses occurred in areas with lower PGV on the west side of the city, and large areas with large values of PGV on the east side had no collapses.

The variation of PGV across a swath of the city (bounded by latitudes 19.35 and 19.45, Figure 14) is illustrated by the profile in Figure 15.

The low intensities on the west are attributed to the presence of rock and shallow soil deposits. The high intensities on the east could be attributed to deep soil deposits from the original lakebed and basin effects. But the fluctuations in the center are not as easy to attribute to the properties of the soils indicated by the soils map in Figure 6.





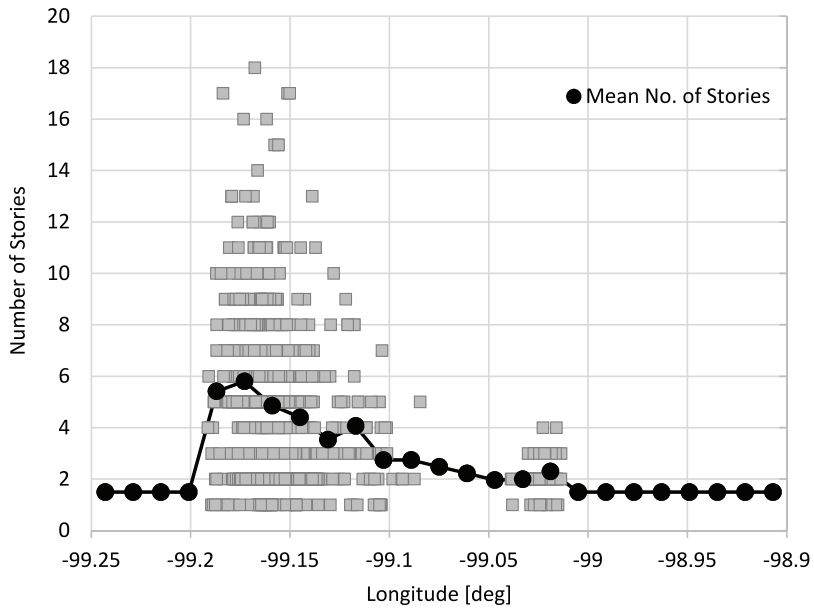
**Figure 15.** Variation of PGV from west to east between latitudes 19.35 and 19.45 degrees.

Driving through the city reveals that taller buildings are concentrated along a rather narrow corridor running nearly N-S near the west edge of the city. Detailed information on density of buildings and building heights is not available to the writers. But we do have the information on building height (number of stories) collected by CICM-SMIE for nearly 2000 buildings. The average number of stories for all surveyed buildings in the swath bounded by latitudes 19.35 and 19.45 (Figure 14) is shown in the profile in Figure 16. Most of these surveyed buildings had fewer than 20 stories.

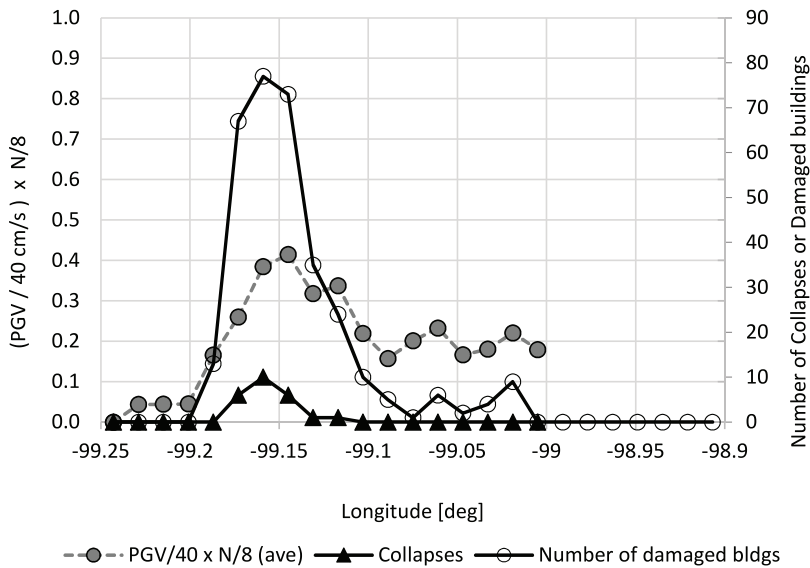
Figure 16 can be thought of as a city “profile.” Near the east and west boundaries of the plot, no information was available but an average height of 1.5 stories, inferred from photographs published by Google, is used. The plot confirms the impression described above that buildings with more than 2 stories concentrate on a 5 km band between longitudes 99.2 W and 99.1 W deg. Given that short 1- to 2-story houses are typically confined masonry structures while taller buildings tend to have flexible (at least in one direction) RC frames, it should not be surprising that the two different types of structures had different performance. We chose to focus on those with frames.

Assuming that building average height is an indicator of the density of RC frames in the city, comparing Figures 15 and 16 would suggest that there was an area in which both demand and RC frame density were high. West of  $-99.2$  degrees longitude, both the demand and density were low. East of  $-99.1$  degrees longitude, demand was high but RC frames are sparse. In contrast, near the meridian at 99.15 W, both demand and building density were high. This can be illustrated by multiplying PGV (normalized relative to 40 cm/s) and number of stories (normalized relative to 8) to obtain a new profile combining both demand and building density (Figure 17).

The number of collapses and damaged buildings near a given meridian is superimposed on the plot in Figure 17 to show that damage concentrated where two rather obvious (in retrospect) factors coincided: RC frame buildings (as opposed to 1- or 2-story masonry houses) and high ground motion intensity (PGV). This figure also implies that matching

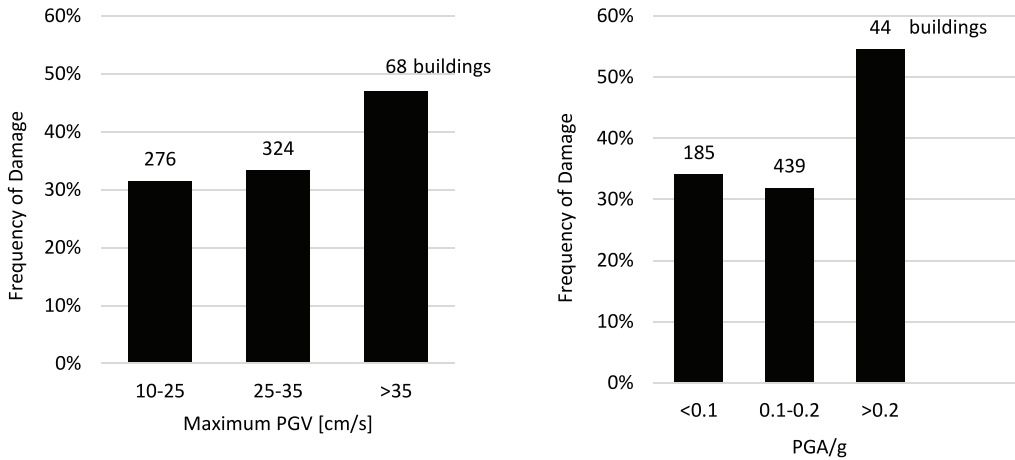


**Figure 16.** Variation of building height from west to east.



**Figure 17.** Variation of drift demand and collapsed buildings.

soil and building period may be less important. Figure 17 emphasizes indirectly the relevance of drift demand because, as stated above, PGV has been reported to correlate well with drift demand.



**Figure 18.** Frequency of damage in buildings with  $N > 2$  versus PGV and PGA.

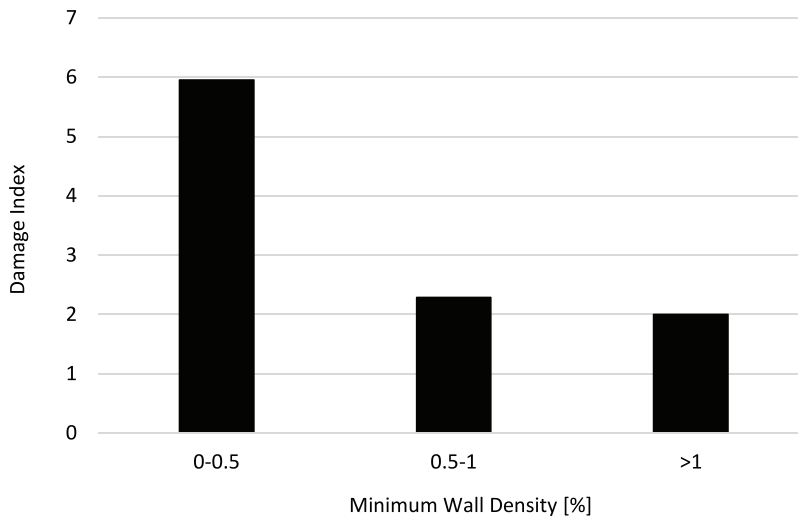
Note: Both plots exclude buildings close to stations that recorded  $PGV < 10$  cm/s. Labels represent number of buildings within each bin.

Two more sets of plots confirm the observations above about the importance of intensity and fundamental period (as a measure of stiffness and mass with direct impact on drift demand). Figure 18 shows that damage frequency among the surveyed buildings tended to increase with both PGV and PGA. Incidentally, reexamining the effect on damage frequency of the ratio of building period to dominant spectral period to focus on only areas with high PGV did not produce better correlation than obtained for the entire dataset.

Figure 19 shows the mean damage index assigned by the writers based on data collected on-site plotted versus wall density (measured as the ratio of cross-sectional area of infill wall<sup>1</sup> to floor plan area). The damage index was chosen to be 1 for little or no structural damage, 5 for moderate damage, and 10 for building collapse and structural failures (Appendix 1). Figure 19 shows that the buildings with larger wall densities performed better despite the modest drift capacity of infill.<sup>2</sup> In addition, it was clear that buildings retrofitted following the 1985 event by adding stiffening elements (often RC infill walls) performed quite well in 2017 (Roselin et al., 2019).

## Conclusions

1. Damage concentrated where two rather obvious (in retrospect) factors coincided: RC frame buildings (as opposed to 1- or 2-story masonry houses) and high ground motion intensity (PGV).
2. The ratio of building period to predominant ground motion period did not have a strong correlation with damage frequency.
3. The evidence available suggests that ground motion intensity (PGV and PGA) drove the occurrence of damage.
4. The evidence available also suggests that stiffer buildings (with more infill walls and stiff retrofit systems) performed better than other buildings.



**Figure 19.** Average damage index versus wall density.

Note: Data used to produce this plot are available at <https://datacenterhub.org/resources/14746> and Design Safe (PRJ-1800 and PRJ-2285). Most walls were masonry infill. RC walls were present in isolated cases. They were treated as being equivalent to produce Figure 19.

## Acknowledgments

The authors would like to thank the Colegio de Ingenieros de Ciudad de Mexico (CICM) and Sociedad Mexicana de Ingenieria Estructural (SMIE) for generously sharing the collected data and for supporting our reconnaissance activities in Mexico City. The writers also gratefully acknowledge the following people and organizations for their support: Luciano Fernandez, UAM; David Muria Vila, UNAM; Hugon Juarez, UAM; Rajesh Dhakal, University of Canterbury; Garcia Jarque Ingenieros; Rodolfo Valles, WSP Group; Antonio Sandoval; Nancy Ariceaga; Roberto Stark; U.S. National Science Foundation, NSF; American Concrete Institute, ACI; New Zealand Society for Earthquake Engineering, NZSEE; and Instituto Nacional de la Infraestructura Fisica Educativa, INIFED.

## Author' note

Santiago Paul is currently affiliated with University of Canterbury, Christchurch, New Zealand.


## Declaration of conflicting interests


The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the National Science Foundation (Award 1810870).

## ORCID iDs

Sergio Brena  <https://orcid.org/0000-0002-7159-7401>

Santiago Pujol  <https://orcid.org/0000-0002-9888-1867>

## Note

1. Values of PGV (and PGA) were obtained from CIRES acceleration records processed in SeismoSpect™ using the default settings including linear baseline correction and filtering with 4th order Butterworth Bandpass filter (0.10–55Hz).
2. If said capacity is exceeded, of course, the apparent benefits of the infill can be compromised and the bare frame may see increased deformation demands and column shear forces where infills fail.

## References

- Aguilar J, Juarez H, Ortega R and Iglesias J (1989) The Mexico Earthquake of September 19, 1985 —Statistics of damage and of retrofitting techniques in reinforced concrete buildings affected by the 1985 earthquake. *Earthquake Spectra* 5(1): 145–151.
- Colegio de Ingenieros Civiles de Mexico (CICM) and Sociedad Mexicana de Ingenieria Estructural (SMIE) (2017a) Information about the earthquake of September 19 2017. Available at: [http://www.cires.org.mx/racm\\_mapa/index.php](http://www.cires.org.mx/racm_mapa/index.php) (accessed 1 October 2018).
- Colegio de Ingenieros Civiles de Mexico (CICM) and Sociedad Mexicana de Ingenieria Estructural (SMIE) (2017b) Resumen Preliminar de Danos de Los Inmuebles Inspeccionados por Las Brigadasdel CICM del SISMO del 19/09/2017. Available at: [http://www.cires.org.mx/racm\\_mapa/index.php](http://www.cires.org.mx/racm_mapa/index.php) (accessed 1 October 2018).
- Donmez C and Pujol S (2005) Spatial distribution of damage caused by the 1999 earthquakes in Turkey. *Earthquake Spectra* 21: 53–69.
- Hassan A and Sozen M (1997) Seismic vulnerability assessment of low-rise buildings in regions with infrequent earthquakes. *ACI Structural Journal* 94(1): 31–39.
- Iglesias J (1989) The Mexico Earthquake of September 19, 1985 —Seismic zoning of Mexico City after the 1985 earthquake. *Earthquake Spectra* 5(1): 257–271.
- Islam S, Sen D, Alwashali H and Maeda M (2018) Rapid seismic evaluation method of existing RC buildings with masonry infill based on earthquake damage. *Proceeding of Japan Institute of Concrete, JCI* 40(2): 1027–1032.
- Laughery L (2016) *Response of high-strength steel reinforced concrete structures to simulated earthquakes*. PhD Thesis, Purdue University, West Lafayette, IN.
- New Zealand Society of Earthquake Engineering (NZSEE) (1988) The September 1985 Mexico Earthquakes: Final report of the New Zealand reconnaissance team. *Bulletin of the New Zealand Society for Earthquake Engineering* 21(1): 3–96.
- O'Brien P, Eberhard M, Haraldsson O, Irfanoglu A, Lattanzi D, Lauer S and Pujol S (2011) Measures of the seismic vulnerability of reinforced concrete buildings in Haiti. *Earthquake Spectra* 27(Suppl. 1): 373–386.
- Pujol S, Irfanoglu A, Gulkan P, Heaton TH, Sozen MA and Laughery L (2018) A potential problem in estimating the drift response of long-period structures. In: *Proceedings of the 11th U.S. national conference on earthquake engineering*, Los Angeles, CA, 25–29 June. EERI.
- Pujol S, Laughery L, Puranam A, Hesam P, Cheng L-H, Lund A and Irfanoglu I (2020) Evaluation of seismic vulnerability indices for low-rise reinforced concrete buildings including data from the 6 February 2016 Taiwan Earthquake. *Journal of Disaster Research* 15: 9–19.
- Riddell R, Wood SL and De La Llera J (1987) *The 1985 Chile Earthquake: Structural characteristics and damage statistics for the building Inventory in Viña del Mar*. Civil Engineering Studies: Structural Research Series No. 534, August. Urbana, IL: University of Illinois at Urbana-Champaign, p. 265.
- Roselin S, Juarez-Garcia H, Dhakal RP and Gomez-Bernal A (2019) (in review) The September 19th, 2017 Puebla, Mexico Earthquake: Final report of the New Zealand reconnaissance team. *Bulletin of the New Zealand Society for Earthquake Engineering*. Available at: <https://bulletin.nzsee.org.nz/index.php/bnzsee/about>
- Servicio Sismologico Nacional (SSN) (2017) Special report on the 19 September 2017 Puebla Morelos Earthquake. Available at: <https://www.sismosmexico.org/informes> (accessed 1 October 2018).

- 
- Shah P, Pujol S, Kreger M, McCabe S and Irfanoglu A (2017) 2015 Nepal Earthquake, damage assessment survey. *Concrete International* 39(3): 42–49.
- Shiga T, Shibata A and Takahashi T (1968) Earthquake damage and wall index of reinforced concrete buildings. In: *Proceedings of the Tohoku district symposium, Architectural Institute of Japan, no. 12*, Tokyo, Japan, December, pp. 29–32 (in Japanese). AIJ.
- Sozen MA (2003) The velocity of displacement. In: Wasti ST and Ozcebe G (eds) *Seismic Assessment and Rehabilitation of Existing Buildings* (NATO Science Series IV: Earth and Environmental Sciences), vol. 29. Dordrecht: Springer, pp. 11–28.
- Stark R (1988) *Evaluation of strength, stiffness and ductility requirements of reinforced concrete structures using data from Chile (1985) and Michoacán (1985) Earthquakes*. PhD Thesis, University of Illinois at Urbana-Champaign, Urbana, IL.
- Stone WC, Yokel FY, Celebi M, Hanks T and Leyendecker EV (1987) *Engineering aspects of the September 19, 1985 Mexico Earthquake*. NBS Building Science Series, 165. Washington, DC: National Bureau of Standards Science.
- Teran-Gilmore A and Bertero V (1992) *Performance of tall buildings during the 1985 Mexico Earthquakes*. Report No. UCB/EERC-92/17. Berkeley, CA: Earthquake Engineering Research Center.
- United States Geological Survey (USGS) (1985) M 8.0—Michoacan, Mexico. Available at: <https://earthquake.usgs.gov/earthquakes/eventpage/usp0002jwe#executive> (accessed 1 October 2017).
- United States Geological Survey (USGS) (2017) M 7.1 – 1km E of Ayutla, Mexico. Available at: <https://earthquake.usgs.gov/earthquakes/eventpage/us2000ar20/executive> (accessed 1 October 2017).

## Appendix I

List of parameters obtained for each building surveyed by the writers ([https://datacenter-hub.org/dv\\_dibbs/view/1723](https://datacenter-hub.org/dv_dibbs/view/1723)):

- Number of Stories Above Ground
- Number of Stories Below Ground
- Year of Construction
- Structural System
- First Floor Height (cm)
- Typical Exterior Column Width (cm)
- Typical Exterior Column Breadth (cm)
- Typical Interior Column Width (cm)
- Typical Interior Column Breadth (cm)
- Typical NS/Parallel Span (cm)
- Typical EW/Perpendicular Span (cm)
- Masonry Wall Thickness (cm)
- RC Wall Thickness (cm)
- Column Area Ratio (%)
- NS/Street Parallel Masonry Wall Ratio (%)
- EW/Street Perpendicular Masonry Wall Ratio (%)
- NS/Street Parallel RC Wall Ratio (%)
- EW/Perpendicular RC Wall Ratio (%)
- Soft Story (Y/N)
- Vertical Irregularities (Y/N)
- Captive Columns (Y/N)
- Discontinuity (Y/N)
- Signs of Dominant Torsion (Y/N)
- Corner Building (Y/N)
- Flat Slab (Y/N)



Waffle Slab, Reticular (Y/N)  
Tie Spacing (cm)  
Hook Type (deg)  
Repair (Y/N)  
Splice Failure (Y/N)  
Crushing (Y/N)  
Bar Buckling (Y/N)  
Pounding (Y/N)  
Shear Failure (Y/N)  
Joint Failure (Y/N)  
NS/Street Parallel Masonry Damage  
EW/Street Perpendicular Masonry Damage  
NS/Street Parallel RC Damage  
EW/Street Perpendicular RC Damage  
Comments  
Report(s)  
Photos, Videos, Media.  
Drawings/Diagrams

The damage classifications used were as follows:

Buildings in which at least one floor or part of the floor lost its elevation were classified as “collapses.” Damage to buildings with at least one structural failure that rendered the structural element defunct was classified as “severe damage.” Buildings without failures but with crack widths in structural elements exceeding 0.13 mm (0.005 in) or structural elements with spalling of concrete were classified as having “moderate damage,” and buildings with hairline cracks not exceeding 0.13 mm were rated as having “light damage.” Damage to masonry infill walls was also classified as “severe,” “moderate,” or “light.” Damage to masonry walls was rated as “severe” if collapse or see-through cracks were observed. Large cracks in masonry walls and flaking of large pieces of plaster were rated as “moderate damage,” and hairline cracks in masonry walls were classified as “light damage.”

## **Appendix 2**

Information collected in survey by CICM and SMIE:

<https://www.sismosmexico.org/informes>  
Address  
Postal Code  
Longitude  
Latitude  
Number of Floors above Ground  
Number of Basements  
Total Collapse  
Partial Collapse  
Differential Settlement  
Inclination  
Structural Damage  
Damage to Non-structural Elements