17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

GEO-SPATIAL ANALYSIS OF REINFORCED CONCRETE BUILDING DAMAGE IN 2017 MEXICO EARTHQUAKE

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Abstract

This paper summarizes analyses of structural damage to reinforced concrete buildings seen after the 2017 Mexico City earthquake. With respect to the 2017 earthquake, the authors are part of a multi-institution National Science Foundation (NSF) RAPID effort that involved several in-field data collection missions yielding a dataset with detailed metadata for nearly 120 buildings. This data has been analyzed in conjunction with a high-density data set of around 1400 buildings from the National Autonomous University of Mexico (UNAM). The focus of analyses includes identifying correlations between building attributes (age, height, column ratio, design vulnerabilities, etc.) and site attributes (soil zone and local seismicity) to observed damage severity.

The presented analyses rely heavily on geo-spatial mapping of data sets as Mexico City, constructed on a lakebed and having a unique soil profile and variance in seismicity, has geographically variable severity of reinforced concrete building damage. Specifically, the research team has leveraged the capabilities of geo-spatial mapping software ArcGIS Pro to investigate damages with respect to geotechnical zones and the PGA and PSA values from an array of ground motion stations active in the region during the 2017 earthquake. Thus, it has been possible to link metadata for geotechnical zone and ground motion for the closest station to each building.

Aside from conclusions about the 2017 Mexico earthquake related to structural damage in reinforced concrete buildings, the authors will share the workflow for data curation and visualization methods for both ArcGIS Pro and MATLAB. These enable raw data from buildings, ground motion stations, and soil zone maps to be rapidly transformed into meaningful data structures, quantitative graphs, and geo-spatial maps. These protocols can be extremely powerful in the aftermath of a subsequent major earthquake to post-process and analyze reconnaissance data in a manner that provides the necessary evidence to support changes in current seismic design codes of practice.

Keywords: 2017 Mexico Earthquake; concrete building damage; post-earthquake reconnaissance; geo-spatial mapping

1. Introduction

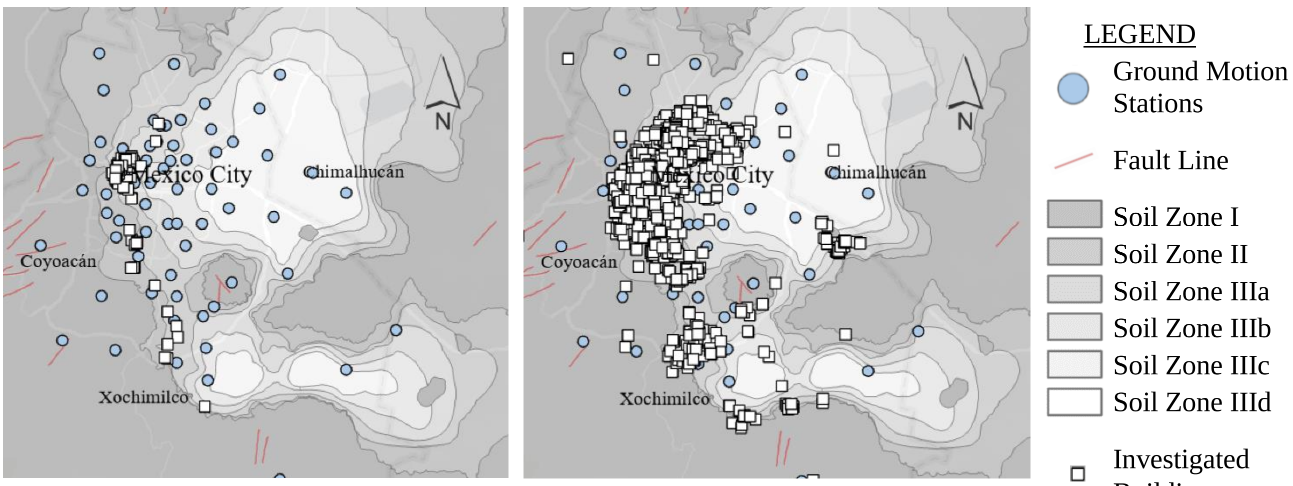
1.1 The Puebla-Morelos Earthquake and Mexico City

The M_w7.1 Puebla-Morelos earthquake occurred on September 19, 2017 at 1:14pm local time, claiming over 300 lives and resulting in 46 structural collapses [1, 2]. The earthquake occurred at a depth of 57 km due to normal faulting and was approximately 60 km southwest of Puebla and 120 km southeast of Mexico City [3]. Mexico City is located in a valley basin surrounded by volcanic mountains. This region is characterized by variable soils and soft clay deposits. On the city perimeter are Zone I soils comprised of relatively high strength volcanic tuffs. In the city, Zone III soils are primarily clay deposits with high compressibility and water content, and the transition Zone II is defined by layers of sand and clay. Of specific concern are soft soils in the lake bed area (Zone III), as they are susceptible to settlement as well as amplification of the horizontal component of the ground motion due to soil-layer resonance particularly due to large distant, low frequency content earthquakes [3, 4].

The 2017 earthquake occurred on the anniversary of the 1985 Mexico City earthquake, which occurred due to thrust faulting and killed between 5,000 and 10,000 people in Mexico City [5]. The 2017 earthquake had higher frequency content than the M_w8.0 1985 ground motion, which was more intense in softer soil zones where natural site periods were similar to the dominant long periods of the ground motion [3, 6]. Because linear response spectra retrieved from ground motion records exceeded the design response spectra and provisions of the existing code, many emergency code changes were initiated after the 1985 earthquake [7]. Among them, seismic design coefficients were increased, strength reduction factors were further reduced, and ductile detailing requirements were made stricter.

1.2 Research Objectives

This study aims to understand potential reasons for building damage during the 2017 earthquake by analyzing two separate data sets collected during reconnaissance missions. MATLAB [8] and ArcGIS Pro [9] (subsequently referred to as ArcGIS) were used to organize metadata for each surveyed building and illustrate relationships between damage severity, structural characteristics, and site conditions. With these tools, data sets can be rapidly visualized and linked with geospatial information such as site seismicity and soil characteristics, as illustrated in Fig. 1. The research was undertaken in part to investigate the adequacy of reinforced concrete (RC) design practices and identify deficiencies observed in the 2017 Puebla-Morelos earthquake. Additionally, a set of analysis protocols was developed that can be used to rapidly analyze building damage from other earthquake reconnaissance data sets.



A) NSF Data Set (~120 buildings) B) UNAM Data Set (~1400 buildings)

Fig. 1 – ArcGIS maps of Mexico City study area

2. Data Analysis

2.1 Data Collection Methods

The National Science Foundation (NSF) RAPID teams consisted of students, faculty, and practitioners affiliated with universities in the United States. These teams collected information for nearly 120 reinforced concrete buildings during two reconnaissance missions following the Puebla earthquake. The data set, henceforth NSF data set, has buildings located primarily on the western side of Mexico City in soil zones II, IIIa, and IIIb, which are indicated by the square markers in Fig. 1A. Investigators gathered detailed metadata for each building including number of stories, location, date of construction, structural system, column and wall ratios, irregularities, failure types, and damage severity for RC and masonry elements. When determining damage severity, the worst case from recorded RC and masonry damage was utilized as described in Table 1.

Table 1 – NSF data set damage categorization

Damage Category	N/A	None	Light	Moderate	Severe	Collapse
Number of Buildings	11	21	12	13	50	2
Description			Hairline cracks, flaking of plaster	Spalling, cracks in walls and joints	Wide and thorough cracks, local structural failure	
Example						

To compare RC buildings to the general building stock in Mexico City, a data set containing a variety of structural systems and compiled by the National Autonomous University of Mexico (UNAM) was analyzed and is illustrated by the square markers in Fig. 1B. Henceforth referred to as the UNAM data set, it consists of approximately 1400 buildings with metadata including number of stories, location, and damage type for each building. Damage in the UNAM data set was classified differently from the NSF data set, and is plotted in this paper in categories of collapse and partial collapse, structural damage (includes damage to structural elements, differential settlement, and residual displacement), non-structural damage, and no damage.

In addition to relationships between damage and structural characteristics, the soil type for each building was extracted using the ArcGIS and ground motion records were collected from approximately 60 accelerometer stations located around Mexico City. A map of ground motion (GM) stations is provided in Fig. 2 and shows the peak ground acceleration (PGA) recorded at each station as well as peak spectral accelerations (PSA) in north/south and east/west directions. PGA and PSA magnitudes are denoted in Fig. 2 by the size of the blue circle markers and the length of the green and yellow bars, respectively. A calculation method was developed in MATLAB was used to determine the nearest station to each building. This enabled the authors to examine relationships between building damage, peak ground acceleration and velocity, and period ratios between a building's natural period and the dominant period associated with the ground motion. ArcGIS images display geospatial information relating damage severity to building characteristics, soil zones, and GM stations while MATLAB plots provide a quantitative way of investigating data correlations.

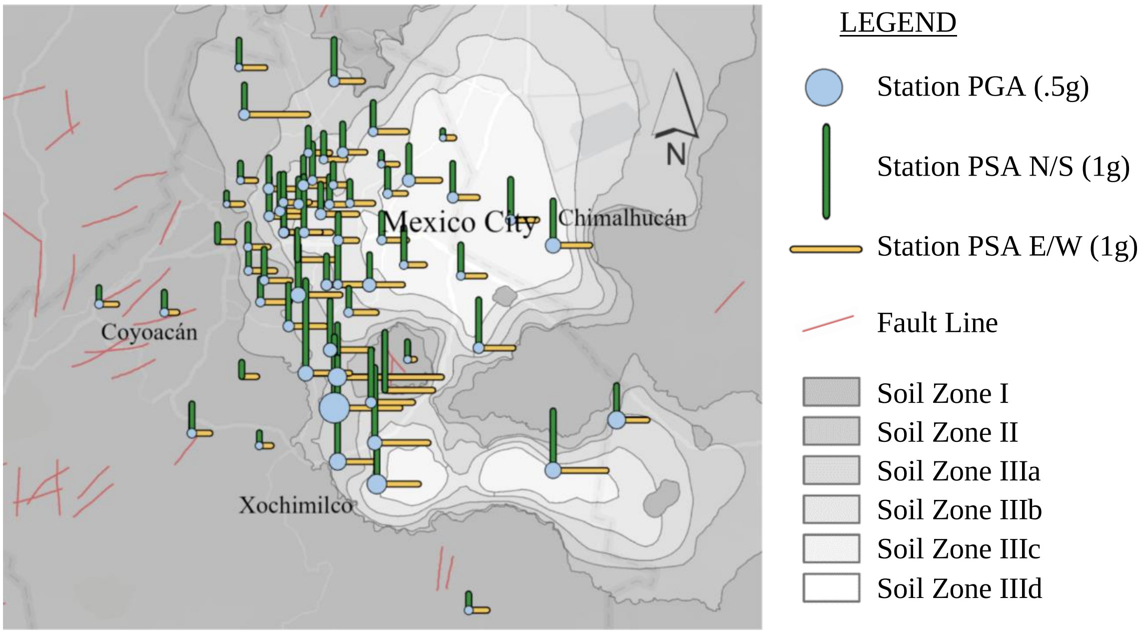
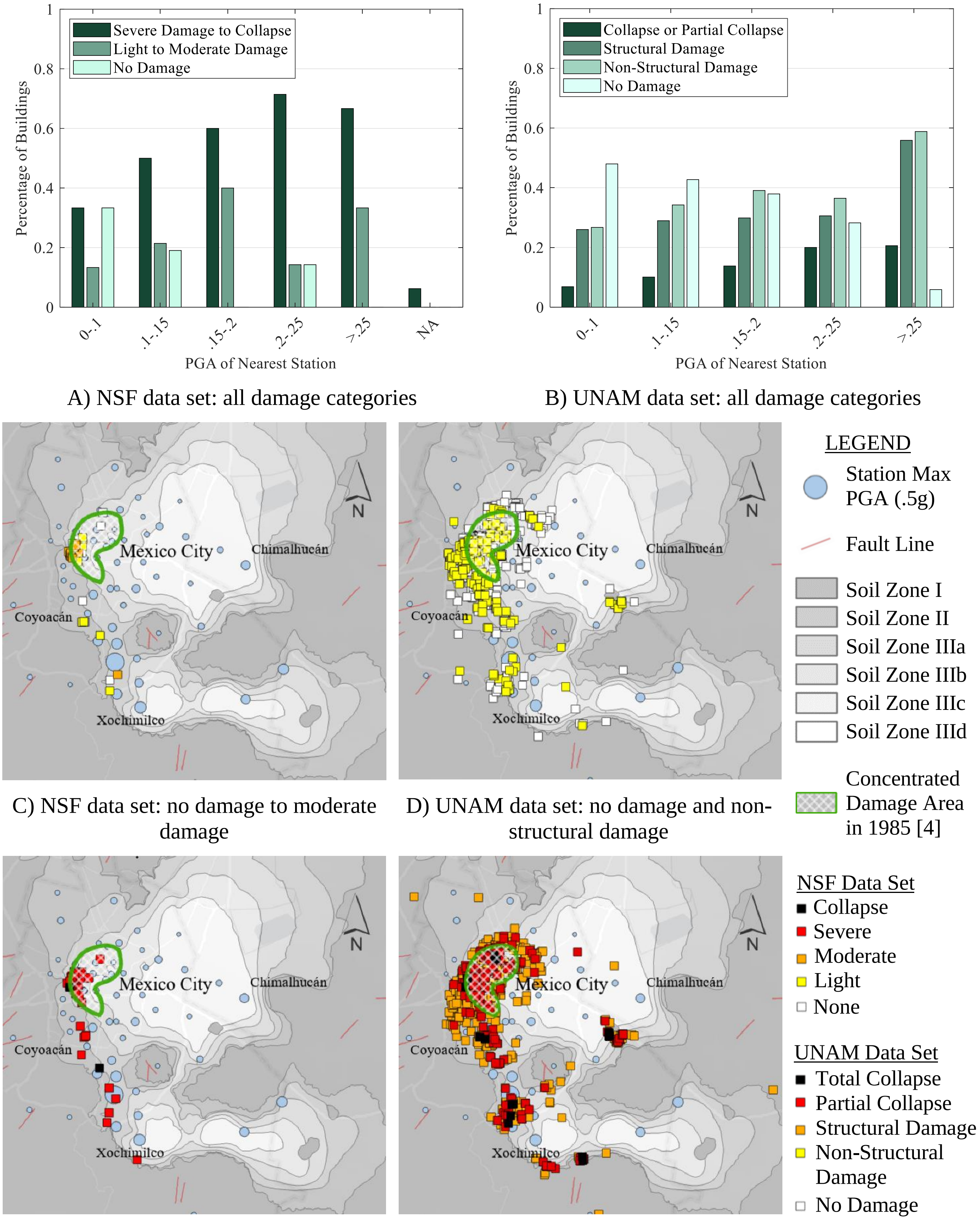


Fig. 2 – Ground motion stations with PGA and PSA values represented

2.2 Ground Motion and Site Analysis

The PGA for the nearest station to each building was plotted against damage severity, as illustrated in Fig. 3A for the NSF data set and Fig. 3B for the UNAM data set. Along the y-axis, percentage of buildings is calculated as the number of buildings characterized by a specific damage category in a PGA range divided by the total number of buildings in that PGA range. Both data sets indicate that increasing PGA values correspond with increasing damage. For reinforced concrete buildings and the general building stock, if the ground motion is more intense, there is a greater quantity of severely damaged buildings and a smaller quantity of buildings in the no damage category. Data was also analyzed using ArcGIS to determine if a similar relationship could be geospatially observed between PGA values and building damage; these maps are shown in Fig. 3C-F. Examination of Fig. 3F indicates a cluster of total and partial collapses in the southwest corner of the image. The poor performance of structures in that location is an example of the trend identified via Fig. 3B as stations near this cluster measured higher PGA values, indicated by larger blue circle markers in the ArcGIS maps.

As shown in Fig. 4, soil zone had a less significant impact than PGA in predicting damage severity. However, PGA values tended to be larger in Zone IIIa, which is where both NSF and UNAM data sets show a slight peak in damage severity. This finding is consistent with observations from the 1985 earthquake, where damage was concentrated in Zone III at sites with dominant ground periods longer than approximately 1.5 sec [3, 7]. Soil-structure interaction in the 2017 earthquake differed from the 1985 event because damage was located primarily in the west and southwest edge of Zone III, while damage in 1985 was clustered in the northwest area of Zone III as noted by the region enclosed with a green line in Fig. 3C-F [3, 4]. NSF reconnaissance teams focused their investigation efforts primarily in Zones IIIa and IIIb, where there appeared to be substantial reinforced concrete building damage.



A) NSF data set: all damage categories

B) UNAM data set: all damage categories

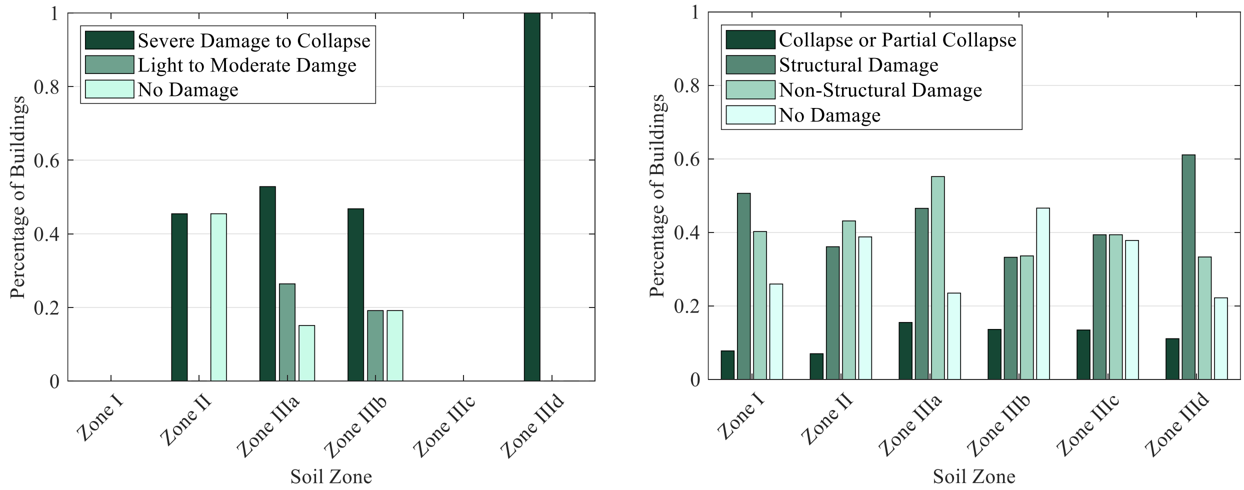
C) NSF data set: no damage to moderate damage

D) UNAM data set: no damage and non-structural damage

E) NSF: severe damage to collapse

F) UNAM: structural damage to collapse

Fig. 3 – Quantitative and geospatial analysis of relationship between damaged buildings and PGA values



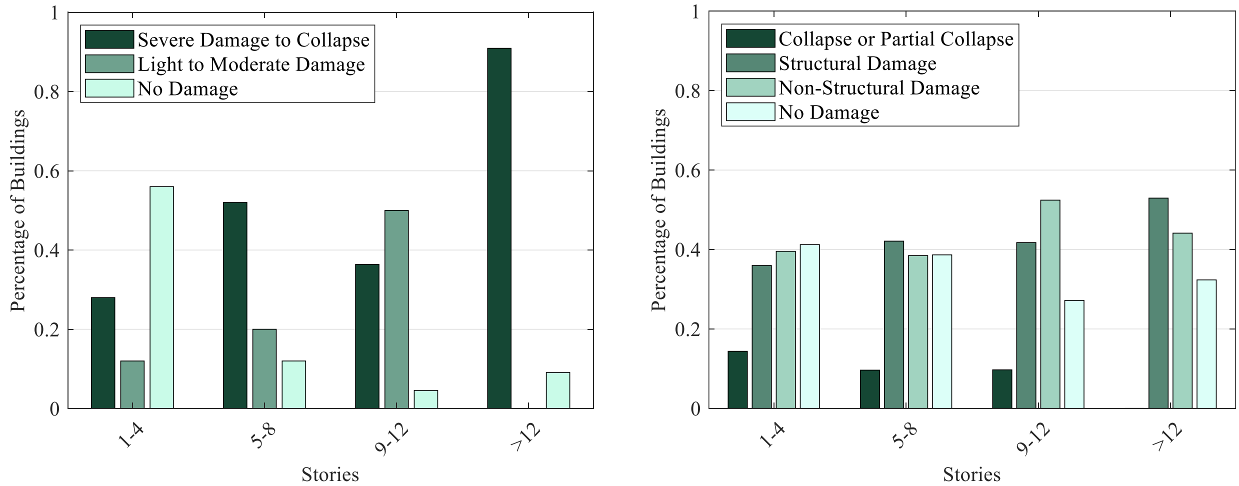
A) NSF data set* B) UNAM data set

Fig. 4 – Damaged buildings in each soil zone

*Only one building was surveyed in Zone IIId

2.3 Investigation of Resonance

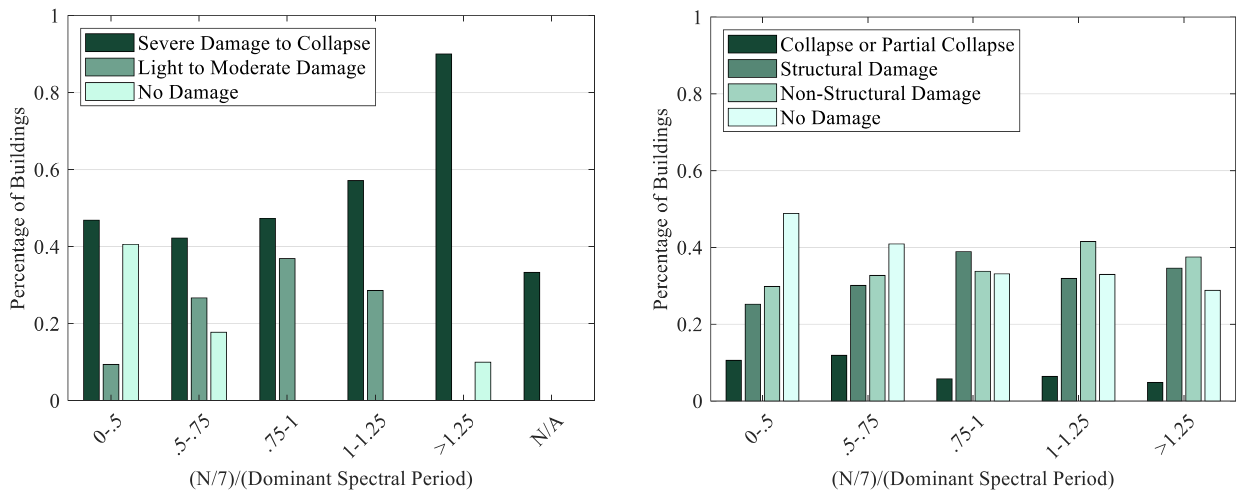
During the 1985 earthquake, resonance compounded damage in buildings of an intermediate height with periods corresponding to the dominant motion of the soft soil zones [6]. Mid-rise buildings also experienced damage because they often lacked the inelastic capacity of tall buildings with high ductility detailing and a fundamental period exceeding 2 seconds, and the overstrength of short buildings with high wall density and a fundamental period less than 0.5 seconds [6]. A preliminary way of investigating resonance in the 2017 event was to determine if damage was concentrated in one story range more than any other. Illustrated in Fig. 5A, RC building damage was more substantial in the 5-8 story range and the >12 story range. However, the >12 story range only has eleven surveyed buildings, six of which are classified under the same address and may be wings of the same building. Therefore, the sample size of the >12 story range in the NSF data set is small and suggests inconclusive results compared to the 5-8 story range. The UNAM data set (Fig. 5B) offers no distinct indication of damage correlated with a specific story range, but a map of damage in the 5-8 story range is provided in Fig. 11C. The 5-8 story range seems to be affected more substantially for reinforced concrete buildings, but the relationship between story range and building damage is not as clear across all buildings types as was observed in the 1985 earthquake.



A) NSF data set B) UNAM data set

Fig. 5 – Damaged buildings in each story range

A more in-depth investigation of resonance was undertaken to determine its role in building damage during the 2017 earthquake. The dominant spectral period was obtained from each ground motion record by identifying the period associated with the peak spectral acceleration. The period of each building was estimated by dividing the number of stories by seven, a method that has been used with relative accuracy for typical buildings in Mexico City [10]. A ratio was taken of each estimated building period to the dominant spectral period of the nearest station. Fig. 6 indicates that resonance did not play a significant factor in the 2017 earthquake because damage is not concentrated near a period ratio of one (T_n =1) in either data set. This was likely because the 2017 event was closer in proximity than the 1985 event and generated a ground motion with higher frequency content than the long period motions from 1985 [3].

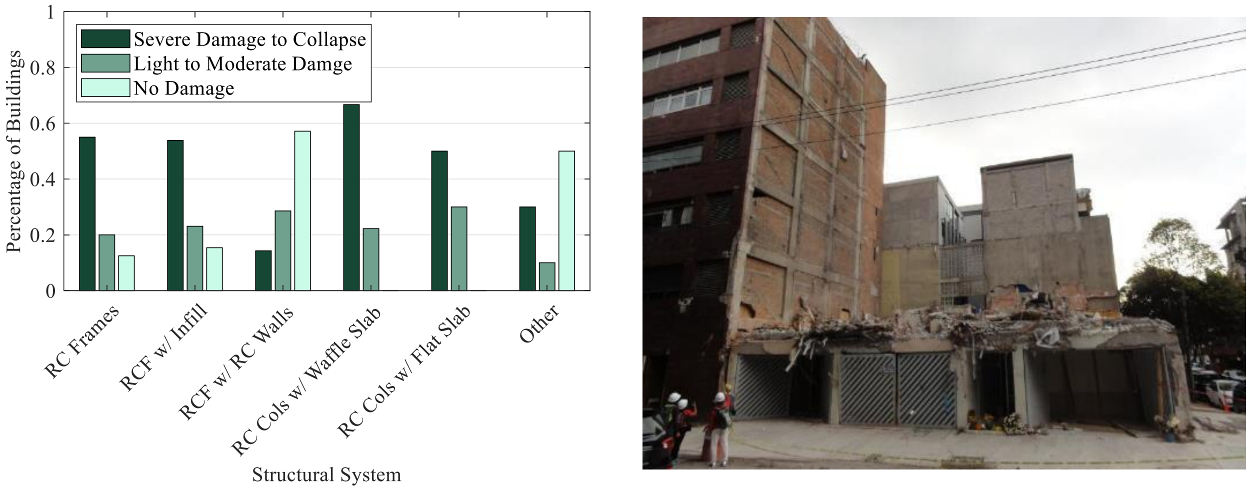


A) NSF data set B) UNAM data set

Fig. 6 – Damaged buildings in each range of period ratios

2.4 Effects of Structural Systems and Irregularities

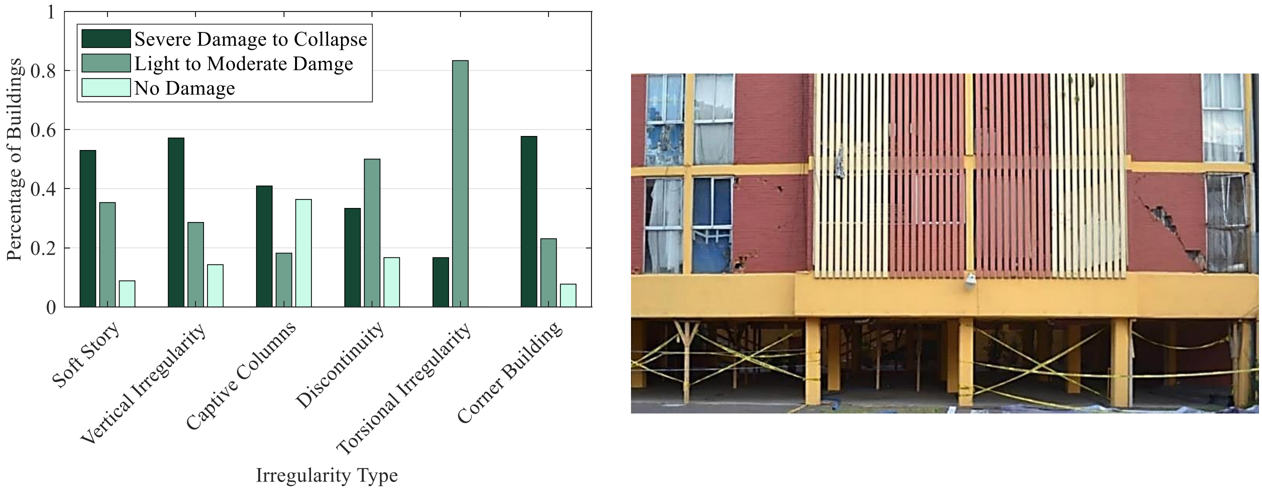
For the NSF data set, the specific reinforced concrete structural system was recorded for each building. Fig. 7A illustrates that RC frames with RC walls performed better than any other concrete structural system. Fig. 7B shows a specific collapse that occurred with a flat slab building, and is one of only two collapses that were recorded in the NSF data set. Additional reconnaissance efforts investigating collapsed buildings [11] reveal that many flat slab systems lacked column heads or drop panels, and flat slab systems were consistently problematic across Mexico City during the 2017 earthquake. 61% of collapsed buildings were flat slab systems [12]. The 1985 Mexico City earthquake also saw significant damage and several failures due to weak flat slab-column connections [4].



A) Damaged buildings with each structural system B) Flat slab collapse

Fig. 7 – NSF data set reinforced concrete structural systems

Fig. 8A demonstrates that soft stories, vertical irregularities, and corner buildings tended to result in more damage to reinforced concrete buildings than other structural irregularities. An example of severe soft story damage is shown in Fig. 8B and a map of buildings with soft stories is provided in Fig. 11A. Many structures in Mexico City include soft stories due to limited space for new construction, necessitating parking space to be placed below buildings thus decreasing the quantity of lateral force resisting elements on the ground floor. Corner buildings are also problematic because windows occupy two faces of the building to capitalize upon outside views at the upper floors or street access at the lower floors, resulting in decreased wall space, torsional effects, and vulnerabilities in both directions.

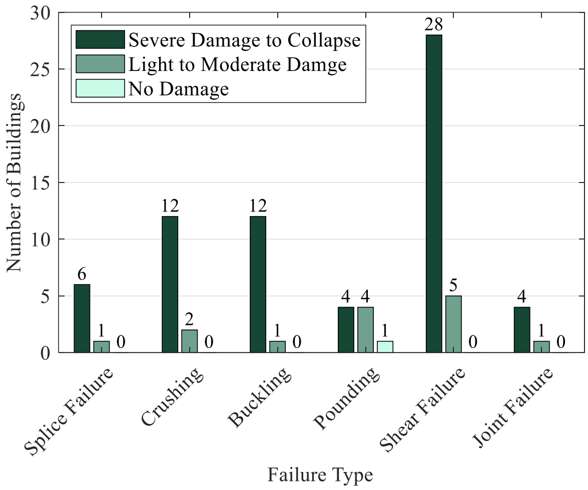


A) Damaged buildings with each irregularity B) Soft story damage

Fig. 8 – NSF data set buildings with irregularities

2.5 Damage Types

The NSF data set includes damage type for each building in addition to damage severity. Many severely damaged structures experienced multiple types of damage, while buildings that experienced no damage are generally not included in Fig. 9A. This graph illustrates that shear was the primary mode of damage, followed by crushing and buckling. Examples of shear and buckling damage are shown in Fig. 9B-9C and a map of buildings that experienced shear damage is provided in Fig. 11B. Although ratios of total column area to floor area can be a predictor of damage [13], the authors' investigation of this metric in the NSF data set suggests that column ratio did not show a clear correlation with building damage for RC buildings in Mexico City.



A) Damaged buildings with each type of failure

B) Shear damage

C) Buckling damage

Fig. 9 – NSF data set categorization of damage/failure type

2.6 Building Ages

The large majority of buildings surveyed by the NSF RAPID reconnaissance teams were constructed before the 1985 earthquake. Fig. 10 shows the number of buildings in each age range and damage category, with insignificant sample sizes in the years following 1985. The lack of data indicates that damage was likely concentrated in pre-1985 buildings because the reconnaissance teams surveyed damaged structures more often than undamaged structures. It is therefore reasonable to assume that newer buildings performed better than older buildings because of updates in code requirements and improvements in design and construction techniques following the 1985 earthquake.

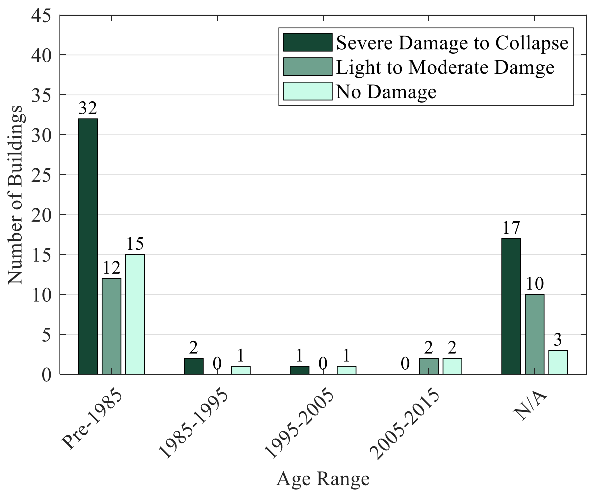
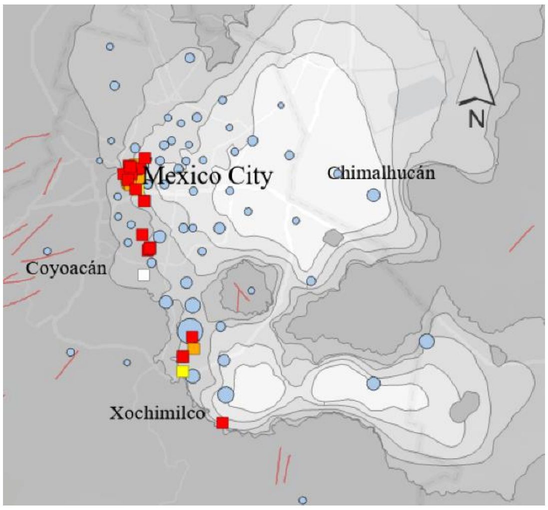


Fig. 10 – NSF data set damaged buildings in each age range

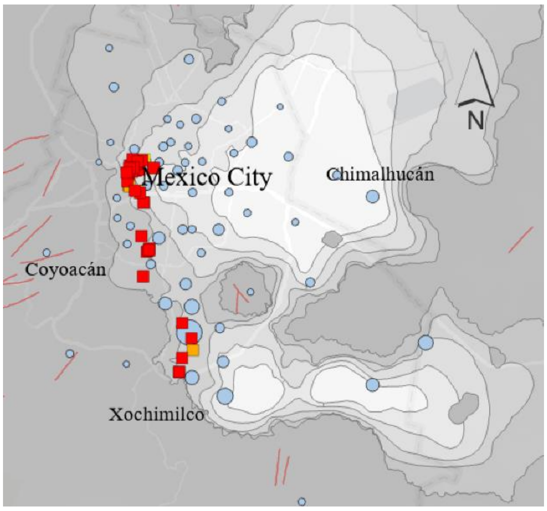
3. Data Curation Techniques and Applications

In addition to analyzing reinforced concrete building damage during the 2017 Puebla earthquake, a purpose of this project was to develop data visualization methods that could be used in future earthquake reconnaissance. The principal software tools used for investigation were MATLAB and ArcGIS.

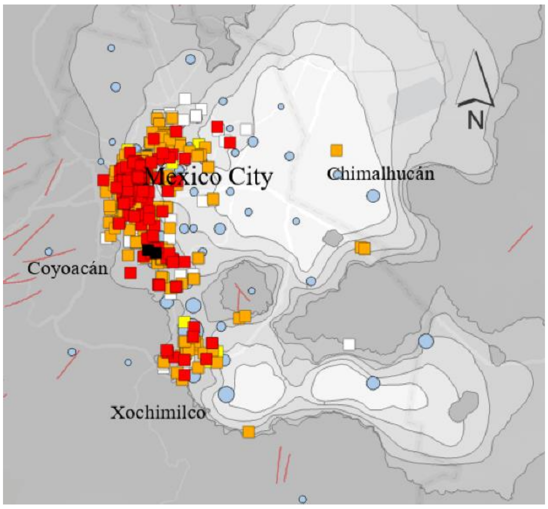
MATLAB and ArcGIS can both be used to partition data sets based on specific parameters. Throughout this paper, MATLAB plots describe relationships between damage and various building or site characteristics. Maps showing damage severity for isolated characteristics are presented in Fig. 11.



A) NSF data set: buildings with soft stories



B) NSF data set: buildings with shear damage



C) UNAM data set: buildings with 5 to 8 stories

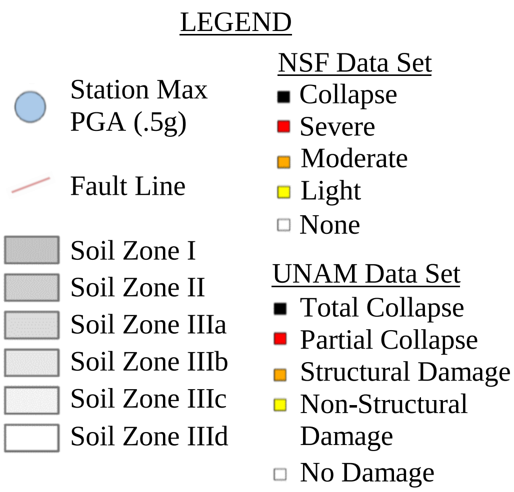


Fig. 11 – ArcGIS maps focused on specific building and damage characteristics

The workflow for developing ArcGIS images and MATLAB plots with multiple (or isolated) parameters is illustrated in Fig. 12 and a description of the steps are as follows:

1. Gather raw data inputs:
   - Building reconnaissance forms, drawings, and photographs describing structural characteristics and damage

- Ground motion data retrieved from accelerometer stations
- Maps containing fault lines and geotechnical zones
- Relevant data about building damage from prior earthquakes in the region to provide a point of comparison to the current seismic event being studied

2. Digitize and compile raw data in Excel spreadsheets
3. Transfer data to MATLAB and ArcGIS
    - MATLAB:
        - Organize building and ground motion station data into data structures
        - Calculate estimated building periods and dominant spectral periods
        - Determine the nearest GM station to each building
    - ArcGIS:
        - Receive and associate building markers with as-built and damage metadata
        - Receive and associate ground motion station markers with values such as PGA and PSA as well as plots of design spectra
        - Extract the soil zone for each building to add to the MATLAB data structure
4. Produce data visualization outputs
    - MATLAB: generate plots to examine the correlation between damage, building characteristics, site and ground motion attributes
    - ArcGIS: develop maps to examine geospatial variance of data

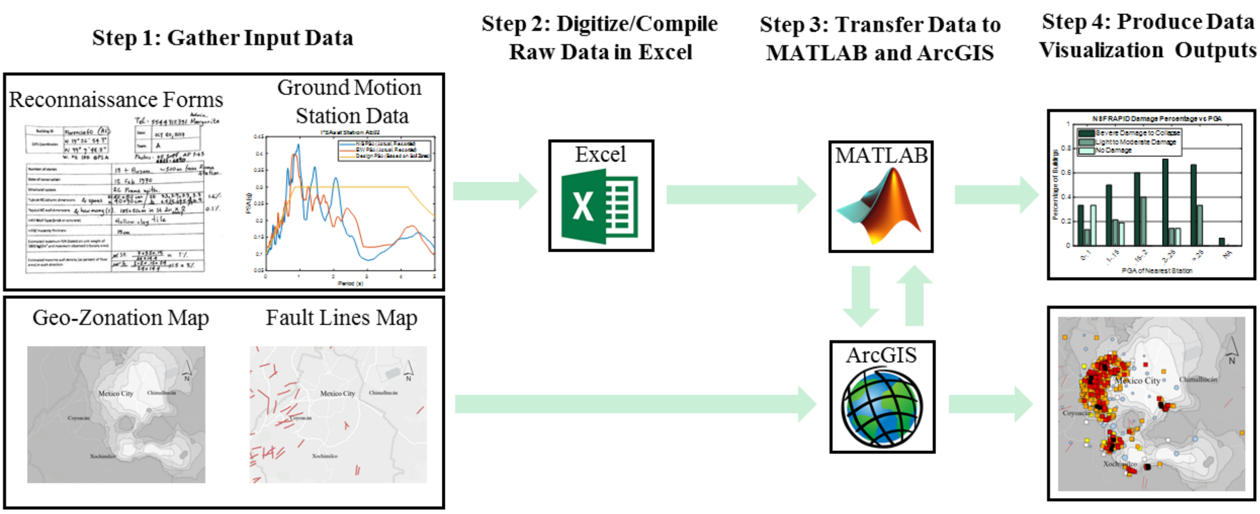


Fig. 12 – Data analysis and visualization process

4. Conclusions

The September 19th, 2017 Puebla earthquake caused extensive damage in Mexico City because of soft soils and high intensity ground motions. After analyzing the NSF data set with approximately 120 reinforced concrete buildings and the UNAM data set with approximately 1400 buildings containing a variety of structural systems, relationships were drawn between damage severity, structural characteristics, and site attributes to determine why certain buildings were damaged more than others. The following trends were noted:

1. Structural damage was more severe for buildings near ground motion stations that measured higher PGA values, indicating that higher intensity ground motions resulted in greater damage for buildings of any structural system.
2. For buildings of all structural systems, damage was weakly concentrated in soil zone IIIa, a soft clay soil adjacent to the transition zone to harder soils.

3. Reinforced concrete damage was more severe in 5-8 story buildings, indicating a relationship with building height, but period ratios suggest that there was little evidence of resonance contributing significantly to damage severity.
4. Reinforced concrete buildings constructed before the 1985 earthquake experienced more severe damage than recently constructed buildings up to current code standards.
5. Soft stories, corner buildings, and flat slab systems resulted in more severe damage than other reinforced concrete systems and irregularities; additionally, damage primarily occurred in the form of shear, buckling and crushing failures.

Data analysis was conducted using MATLAB and ArcGIS. The research team found that these software programs were efficient ways to transform data into meaningful visualizations. The data processing methods developed in this project can be implemented following future earthquake reconnaissance missions.

5. Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 1811084. Any opinions, findings, and conclusions or recommendations expressed in this presentation are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors would like to thank Cal Poly affiliated contributors: Rachel Chandler, Lauren Benstead, Garrett Hagen, S.E., and William Rosenblatt, as well as the other university partners on the collaborative NSF grant.

6. References

[1] Galvis F, Miranda E, Heresi P, Dávalos H, Silos J (2017): Preliminary statistics of collapsed buildings in Mexico City in the September 19, 2017 Puebla-Morelos earthquake. *EERI Puebla, Mexico Earthquake Clearinghouse.*

[2] Díaz A, Murren P, Walker S (2017): 32 years after Michoacán: preliminary reconnaissance observations in the aftermath of the September 19, 2017 Puebla-Morelos earthquake. *EERI Puebla, Mexico Earthquake Clearinghouse*.

[3] Mayoral J, et al. (2017): Geotechnical engineering reconnaissance of the 19 September 2017 Mw 7.1 Puebla-Mexico City earthquake. *Geotechnical Extreme Events Reconnaissance Association.*

[4] Butcher G, Hopkins D, Jury R, Massey W, McKay G, McVerry G (1988): The September 1985 Mexico earthquakes: final report of the New Zealand reconnaissance team. *Bulletin of the New Zealand Natl So for Earthquake Eng.*

[5] Weiser D, Hunt J, Jampole E, Gobbato M (2018): EERI earthquake reconnaissance team report: M7.1 Puebla, Mexico Earthquake on September 19, 2017. *EERI Puebla, Mexico Earthquake Clearinghouse*.

[6] Meli R, Ávila JA (1989): The Mexico earthquake of September 19, 1985 – analysis of building response. *Earthquake Spectra*.

[7] Esteva, L (1988): The Mexico earthquake of September 19, 1985 – consequences, lessons, and impact on research and practice. *Earthquake Spectra*

[8] MATLAB Release 2019a, The MathWorks, Inc., Natick, Massachusetts, United States.

[9] ESRI 2018. ArcGIS Pro: Release 2.5. Redlands, CA: Environmental Systems Research Institute.

[10] Stark, R (1988): Evaluation of strength, stiffness and ductility requirements of reinforced concrete structures using data from Chile (1985) and Michoacán (1985) earthquakes. *Ph.D. Thesis, University of Illinois at Urbana-Champaign, Illinois.*

[11] Ruiz Garcia J (2017): Observations from the September 19, 2017 (M_w=7.1) Puebla-Morelos earthquake in Mexico City. *EERI Puebla, Mexico Earthquake Clearinghouse*.

[12] Datta, A (2019): 2017 Mexico City earthquake: analyses of reinforced concrete building damage. *California Polytechnic State University, San Luis Obispo.*

[13] Hassan A, Sozen M (1997): Seismic vulnerability assessment of low-rise buildings in regions with infrequent earthquakes. *ACI Structural Journal 94(1), 31-39.*

