Identification of the highest risk buildings in Mexico City

Eduardo Reinoso
Pablo Quinde
Marcial Contreras
David Gómez
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For additional information, please contact:

United Nations Office for Disaster Risk Reduction (UNDRR)
9-11 Rue de Varembé, 1202 Geneva, Switzerland, Tel: +41 22 917 89 08
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Authors
Eduardo Reinoso, Institute of Engineering, UNAM, Mexico City, Mexico
Pablo Quinde, Institute of Engineering, UNAM, Mexico City, Mexico
Marcial Contreras, ERN International, Mexico City, Mexico
David Gómez, ERN International, Mexico City, Mexico

Abstract

The timely estimate of human and economic losses due to natural events can effectively help decision-makers develop mitigation actions to avoid these losses. In recent years, various entities and governments have seen the need to improve and increase the information related to natural risks, to develop mitigation measures of risks for various sectors of the society.

The evaluation of the seismic risk in Mexico City requires gathering the characteristics of more than two million buildings, specifically, the structural conditions that increase the damage probability, such as soft story, corner effect, plan irregularity, among others. These characteristics are relatively easily recognizable for a trained structural engineer, although the building database's size makes this task titanic without the help of technology, such as machine learning.

This article summarizes the seismic risk analysis of Mexico City, based on a detailed database constructed with information provided by the city but also with tools such as geomatics and machine learning. The most unfavorable seismic scenarios and structural characteristics that decrease the resilience of the city are shown. The objectives are to propose response plans for any given future earthquake, to develop prevention measures and to increase the city's resilience, starting from a real and reliable database of vulnerable buildings.

Keywords: Seismic risk, mitigation, structural vulnerability, seismic resilience
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Introduction

Within the seismic design guidelines and regulations worldwide, the obvious ones are that governments require that new buildings meet the minimum, state-of-the-art standards contained in the regulations. However, it is highly unlikely that government incentives will increase structural performance and design structures to higher standards than those minimally required by seismic regulation to increase seismic resilience. Indeed, another worldwide common practice is that the seismic regulations are not retroactive, so old buildings, which do not meet modern design requirements, do not need to be strengthened to mitigate structural risk.

The issue of seismic mitigation is complex since it is very expensive and technically complex, and it is not always clear that a lot of money should be spent strengthening structures to meet high standards that will be tested within its lifespan to an unlikely future earthquake. In different experiences worldwide, it has been seen that the problem of mitigation is not only the cost but who pays it and how this cost is distributed, which becomes a bottleneck for the solution. It is even more complex for decision-makers to determine which buildings should be reinforced, assuming that there is always a very large portfolio of exposed assets, as in Mexico City, where there are more than two million buildings to assess.

According to the UN so far this century, although earthquakes are not the events that affect the greatest number of people (these being floods), they are the ones that kill the most people as a percentage of the rate of mortality from natural phenomena worldwide, corresponding to 58% (ie. 721,000 human losses). For example, in the Northridge earthquake in 1994, 33 people lost their lives and direct losses were estimated at $ 45-55 billion. The 1995 earthquake in Kobe, Japan, caused 6,300 deaths, with direct losses estimated at more than $ 120 billion. While in Mexico the earthquakes of September 2017 caused 369 fatalities and losses of 2 to 4.5 billion dollars (Capraro. I, 2018). For this reason, numerous public and private entities have taken the initiative to propose novel solutions to reduce the impact of earthquakes on buildings as a consequence of strong ground motions. However, these initiatives have mostly resulted in building codes and standards that focus on new buildings and do not consider improving the structural safety of existing ones.

It is necessary to explore several possibilities; for example, in the United States, the CEA (California Earthquake Authority) can give an economic aid of up to $ 3,000 and a 25 percent reduction in subsequent insurance premiums. On the other hand, it is necessary to consider the cost-benefit of mitigation. Sometimes it will be worth considering the cheapest and simplest measure, even if this measure is not the best, or choose the best solution that gives the best long-term results, even if it is not the cheapest.

To identify the buildings in Mexico City with the highest risk, besides the characterization of seismic scenarios, it is necessary to analyze the seismic response of more than two million buildings. Apart from the structural system, the number of stories and the year of construction, it is necessary to gather the structural pathologies that aggravate the seismic performance and increase the probability of damage, such as soft stories, corner asymmetry and plan irregularity. These characteristics are easily distinguishable for a structural engineer when inspecting a building, but the city's size makes this task impossible without the help of technology, such as computer machine learning and image processing.

This article proposes a methodology to select, from the entire universe of buildings in Mexico City, those that have the highest seismic risk. The main idea is to provide the decision-makers
precise information on which buildings should focus the mitigation efforts to reduce building vulnerability and increase the city's resilience and resourcefulness. To achieve this objective, four steps were followed:

A. Construction of a database of all housing buildings in Mexico City, with particular emphasis in those located over the lakebed zone.
B. Statistics of detailed damage from past earthquakes to identify the structural pathologies most commonly present in buildings with severe damage. An area in downtown (Roma and Condesa neighborhoods) was used as a case-study since it is a zone where damage due to earthquakes has been very frequent.
C. A full seismic risk analysis of housing buildings in Mexico City.
D. To propose a methodology to identify those buildings with the highest risk in the lakebed zone of Mexico City.

Finally, an analysis of the public policies in Mexico City regarding seismic resilience of the infrastructure of housing sector was carried out. It is necessary to clarify that, despite showing the results in maps and images, the final list of buildings with their exact location will not be presented since it is confidential information managed by the Institute of Construction Safety of Mexico City.

Earthquake risk assessment

The fundamental objective of the probabilistic seismic risk assessment (PSRA) is to determine the probability distributions of the losses that may suffer the exposed assets, for a given return period, as a consequence of the occurrence of natural hazards, rationally integrating the uncertainties that exist in the different parts of the process. The probabilistic risk analysis involves uncertainties that cannot be ignored and must be propagated throughout the PSRA process (ERN Latinoamérica, 2005). To estimate the seismic risk, three steps are required, which are described below:

A. Hazard evaluation: It is the set of events, with their respective frequencies of occurrence, that comprehensively represent the corresponding hazard. Each event contains the spatial distribution of parameters that allow the construction of the probability distribution of the intensities produced by its occurrence.

B. Definition of the inventory of exposed assets: The inventory of exposed assets must be defined, specifying the precise geographical location of the exposed asset plus the following parameters:

- Physical value or replacement cost of the asset
- Estimated number of occupants
- Structural type

C. Structure vulnerability: A vulnerability function must be assigned to each one of the structural types. This function characterizes the behavior of the building during the occurrence of the earthquake.

Seismic risk analyzes are essential to increase the resilience of a certain area. With a correct interpretation of the results of a PSRA, mitigation and emergency management plans can be established since it is possible to estimate probable losses and areas with a concentration of structural damage for certain seismic scenarios.
Seismic hazard and soil effects of Mexico City

Because the uncertainties involved in predicting a seismic scenario occurrence are very high, the probabilistic seismic hazard assessment (PSHA) is used to involve these uncertainties within the hazard model. This is done through seismic probabilistic models and ground motions predictions equations (GMPE) that allow estimating the intensity of an earthquake at a certain site based on its magnitude and the distance between the source and the site of interest.

In a PSHA is necessary to have information on all the seismic regions that contribute to the seismic hazard of the site under study, in terms of their geometry, seismicity and GMPEs. The standard procedure to carry out the PSHA is as follows:

1) Characterization of the seismological regions where earthquakes are generated in terms of their geometry.
2) Determination of the seismicity from the historical earthquakes that occurred on the defined regions (seismic catalog). Additionally, gathering information on neotectonics and paleoseismology studies of the region. Seismicity is established through a magnitude recurrence curve, which is a specific relationship for each region, indicating the exceedance rate of a given magnitude.
3) Selection of the GMPEs that allow a complete characterization of the hazard at the site. Depending on the analysis, GMPEs may be a function of acceleration, velocity, displacement, duration, among others.
4) Finally, the uncertainties associated with the location, magnitude and attenuation of the strong ground motion are combined, obtaining a hazard curve that indicates the probability that a specific intensity will be exceeded in a given return period.

Mexico's seismic hazard has been analyzed for several years. A pioneering work was carried out by Esteva in 1968, and it is the first seismic hazard study worldwide (Esteva, 1968). Since then, and as the information and knowledge have increased, several studies have been developed to detail the seismic hazard in Mexico, including the site effects in Mexico City (Ordaz and Reyes, 1999; Reinoso and Ordaz, 1999; Arroyo et al., 2010; Singh et al., 2015; Ordaz and Arroyo, 2016). Several of these contributions can be seen reflected in the SASID software that is part of the Mexico City Building Code (NTCDS-CDMX, 2021).
Figure 1. Seismic Hazard maps for Mexico City for a return period $Tr = 250$ years and for four structural periods ($Te$) indicated in each chart (PGA, 0.5, 1.0 and 2.0s).

Because the information is very large and it is not the objective of this article, a detailed description of the PSHA of Mexico's characteristics will not be included. Figure 1 shows the
PSHA maps for Mexico City for structural periods (Te) equal to PGA, 0.5, 1.0 and 2.0s, and for a return period of Tr=250 years.

For some frequencies, the amplification can be up 500 times to epicentral sites and up to 100 times the observed at the hill zone. As stated by Ordaz et al., 1988, Singh et al., 1988 and Reinoso and Ordaz, 1999, the lakebed zone soil responds approximately as the one-dimensional theory predicts. Some sites could reach dominant periods as large as Tg = 5.0s.

Although with a PSHA-type analysis, the combined probability of occurrence of all events is considered, it loses sight of the “design earthquake” (McGuire, 1995), which is a useful concept for finding seismic scenarios for seismic hazard purposes. To find the earthquakes that best represent a region’s seismicity, the seismic disaggregation is used, from which a magnitude (M) and distance (R) associated with design events for different seismic sources are obtained. Figure 2 shows the seismic disaggregation for Tr = 250 years at the CU station (located in form soil) and SCT (Tg = 1.9s) for PGA (maximum ground acceleration).

Figure 2. Seismic disaggregation graphs for the CU and SCT stations, for a return period Tr = 250 years.

Figure 2 shows that the “design event” for station CU is an earthquake of Mw = 7.8 at R = 100km (an intermediate-depth earthquake). There are two critical scenarios for the SCT station: an earthquake Mw = 8.2 at a distance of R = 300 km (subduction earthquake) and another one with Mw = 7.8 at R = 100km (an intermediate-depth earthquake).

Seismic scenarios

The seismic hazard in Mexico City depends on the occurrence of various types of earthquakes, especially due to its site effects which amplify the strong ground motion (Reinoso and Ordaz, 1999). Consequently, there is no single seismic scenario that fully estimates structural damage, and therefore for decision-makers to organize risk mitigation plans. The assessment of critical scenarios has some limitations and uncertainties, such as the number of simulations required to achieve convergence, epistemic and random uncertainty in vulnerability models and GMPEs, and the consideration of the earthquake’s rupture geometry (Silva, 2016). These uncertainties have been considered in this project so that three groups of seismic scenarios were used: 1) Scenarios associated with the probabilistic seismic hazard, 2) scenarios associated with results of estimated maximum and recurring losses, and, 3)
historical, well known seismic scenarios and their consequences (Table 1). These selected scenarios provide a whole set that represents the seismic risk in Mexico City, from which it is possible to propose mitigation plans.

Table 1. Historical earthquakes analyzed.

<table>
<thead>
<tr>
<th>Date</th>
<th>Longitude</th>
<th>Latitude</th>
<th>H (km)</th>
<th>Mw</th>
</tr>
</thead>
<tbody>
<tr>
<td>19/11/1912</td>
<td>99.83W</td>
<td>19.33N</td>
<td>60</td>
<td>6.9</td>
</tr>
<tr>
<td>03/06/1932</td>
<td>104.42W</td>
<td>19.57N</td>
<td>20</td>
<td>8.2</td>
</tr>
<tr>
<td>28/07/1957</td>
<td>99.13W</td>
<td>16.21N</td>
<td>25</td>
<td>7.6</td>
</tr>
<tr>
<td>11/05/1962</td>
<td>99.85W</td>
<td>16.9N</td>
<td>25</td>
<td>7.1</td>
</tr>
<tr>
<td>14/03/1979</td>
<td>101.27W</td>
<td>17.81N</td>
<td>49</td>
<td>7.6</td>
</tr>
<tr>
<td>19/09/1985</td>
<td>102.94W</td>
<td>18.08N</td>
<td>15</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Exposure

Description of the database

In this work, the building database for risk assessment was built from the 2020 version of the Mexico City cadaster, published by the Open Geographic Information System of Mexico City (SIGCDMX) and the Secretariat of Urban Development and Housing (SEDUVI). This database contains 1,129,485 building units, most of them are individual buildings, but some of them correspond to neighborhoods that contain buildings with similar characteristics in all 16 municipalities of the city.

An analysis of the geographic space, soil and historical buildings damage allows identifying the zones with high seismic hazard and reducing the search area for vulnerable buildings. Figure 3 shows Mexico City and the 2020 official cadastre (yellow) and the limit of two major zones according to the site effects: hill zone and lakebed zone. Since the strong ground motion at the hill zone has been, and it is expected to be, relatively low, this study is focused only on buildings located at the lakebed zone showed in Figure 3. This fact allows an important reduction of the number of buildings to be analyzed.
Figure 3. Mexico City: cadaster (yellow) and lakebed and hill zones.

Figure 4 shows the statistics of occupancy of buildings in Mexico City before and after the 1985 earthquake. As can be seen, housing predominates, a sector that grew 9.5 percent (140 million square meters) compared to what was built before 1985, followed by industrial and commercial offices. The methodology proposed in this paper will focus only on housing buildings located in the lakebed of Mexico City.

Figure 4. Construction areas built for the different types of occupancies found in the Mexico City buildings database.
The building’s information of the 2020 official cadastre is limited if it is to be used for earthquake risk assessment, so the exposed assets database’s must be completed. The building information included in the Mexico City official cadastre is: the year of construction, number of stories, construction area, occupancy of the building and information that can be related to the structural system. The correct description and characterization of the structures are fundamental for elaborating and assigning vulnerability functions, which describe the structures' performance for different intensity levels.

The year of construction was taken directly from the city cadastre without any modification. Unfortunately, the number of stories and occupancy have various inconsistencies, and their information is unreliable. To have an adequate buildings database for seismic risk purposes, Geomatic and Machine learning techniques were used to correct the information and to obtain additional characteristics, allowing the estimation of the vulnerability with less uncertainty.

**Acquisition of building data**

The acquisition of detailed building data was carried out for all the exposed assets only in the lakebed zone of Mexico City, as explained next.

**Building’s height**

The number of stories was obtained from the cadastre but also comparing with the building's height, based on the difference between the digital surface and terrain models' elevations. This parameter was obtained from INEGI's high-resolution public satellite images and the Japanese agency's digital surface model (data from 2017). The terrain and surface models differ in the frequency band of the electromagnetic spectrum with which they were obtained, so the terrain model is receptive only to topography and the surface model perceives significant diffractors (buildings and vegetation).

The mesh of height points was interpolated at 2m and crossed with each property's plant to obtain the statistics of the heights measured within each property. We found that the median value plus one standard deviation for buildings smaller than 45m, and median value for larger buildings, are a reasonable measure of the building's height. Figure 5 shows the height model used in this project, taking the results of Cuauhtémoc municipality as an example.

*Figure 5. Visualization of the point cloud of the digital surface model (left) and heights levels of properties for the Cuauhtémoc Municipality (right).*
Occupancy of buildings

The type of occupancy is relevant for the vulnerability assessment of structural, non-structural elements (walls, installations, and non-structural components) and contents (furniture, equipment, among others). The type of occupancy was recognized in facade images using a computer vision model trained in the “Places2 database” (Zhou et al., 2017), which contain 365 categories of interior and exterior uses, of which 150 relevant were chosen for this work, which was grouped into four types of occupancies: a) housing and hotel, b) commercial, c) office and d) health. The mixed type of occupancy (housing and commercial in the first story) is particularly important because of its probability of having a first soft story.

First soft story

The first soft story (FSS) is a structural pathology caused by severe stress concentration in the first story, due to a large difference in stiffness between the first story and the rest of the building. As shown in Figure 6, walls may not be continuous along the building's height for architectural, functional or commercial reasons (Yön et al., 2017); creating the soft story that usually is presented on the first floor.

Figure 6. First soft story (FSS): a) where there is no FSS and therefore no change in the structure (left), b) with some walls on the ground floor and therefore light effect of FSS (center), and c) with a heavy FSS effect since there are no walls on the ground floor (right).

The FSS condition is recognizable from the façade, so a computational vision model was trained in three labeled photo arrangements to indicate whether the facade showed a FSS or not, based on the database of building inspections (ERN, 2017) that has 16,641 tagged photographs of inspected buildings.

With each database, a convolutional neural network model was trained, built on the architecture and weights of the VGG16 model (Simonyan and Zisserman, 2015). The average precision of the three computer vision models for identifying the first soft story condition in facade photographs is 77%, which we consider acceptable concerning the base uncertainty of 87%, and that the model is conservative.

Corner asymmetry

A building located in a corner could be more vulnerable, given the architectural and structural characteristics required by this corner location. The structure may present large eccentricities between the center of stiffness and the center of mass, causing excessive torsion throughout the building floor. Figure 7 shows a lateral view of a structural configuration with a corner asymmetry. This structure has two adjoining walls (stiff elements) on two sides and two facades (flexible elements), which can generally be composed of walls with multiple openings for windows and doors, or maybe with no walls at all.
The structures with a corner condition were performed as follows:

1) Taking the polygons of blocks and buildings as a reference, the properties contained in each block are identified, such that the block polygon contained the centroid of the buildings.

2) For each corner of the block, the closest vertex of the property was found. This property was assigned the status of corner.

3) If the property covers 90% of the block area and has three or more facades, it is considered an isolated building that occupies the entire block.

4) To avoid errors derived from the sub-segmentation of the polygons of buildings and blocks, geometric simplifications were applied to reduce the number of vertices.

This algorithm may generate errors in blocks with curved sides but is was not corrected since there are very few curved sides in Mexico City.

Buildings vulnerability

Assessing the vulnerability to understand the causes of disasters and mitigate their impacts can become a complex concept that involves social relationships and processes (Bankoff et al., 2004). However, it is necessary to understand the impact of a natural hazard over social and human-environmental processes. Regarding the seismic risk analysis shown in this article, only the physical vulnerability of the buildings was analyzed. The most accepted definitions of physical vulnerability include the idea that it is the system's susceptibility to suffer damage due to its interaction with potentially dangerous external and internal processes (Corsanego and Petrini, 1990; Dolce et al., 1994; Calvi et al., 2006).

To reduce the uncertainty in estimating structural vulnerability, it is necessary to use information associated with model laboratory tests or real damage statistics. In this project, the statistics of the buildings damaged in Mexico City after the 1985 and 2017 earthquakes were used.

The results of a detailed analysis of the damage of the 2017 earthquake are shown for a group of buildings located within downtown. These results, together with the damage statistics reported in the entire lakebed zone of Mexico City of the 2017 earthquake and past
earthquakes, were used to improve the information of the database of buildings characteristics used in the estimation of the seismic risk shown in this work.

Damage statistics of the September 19, 2017 earthquake

This section summarizes the analysis of the damages reported after the September 19, 2017, Mexico intraslab-earthquake, whose epicenter was located between the limits of Puebla and Morelos states, 120 km away from Mexico City (Singh et al., 2018). Heavy damage was reported in Mexico City, where 39 buildings collapsed, 42 had partial collapses, and more than 800 were severely damaged.

The statistics presented in this work are focused only on the Roma and Condesa neighborhoods (study-case zone) that have historically concentrated a large part of severe damage after intense earthquakes, including the 2017 earthquake, we believe that this results are a good example of the entire lakebed buildings database. In this study-case zone, nine buildings collapsed in an area of approximately 1.0 km². However, most of the buildings in this area remained unharmed despite showing similar structural characteristics to those severely damaged.

Reinoso et al., 2021 showed that structural pathologies were critical for the building damage reported after the 2017 earthquake. In that research, soft story and corner asymmetry were studied in detail, from 1923 buildings located in the Roma Neighborhood. This database contained buildings with null damage, medium damage and collapse cases in a zone limited by a 600m radius. Reinoso et al. (2021), showed that both characteristics, first soft story and corner asymmetry are critical and show very poor structural performance. For this analysis both damaged and undamaged buildings with similar structural types and characteristics were considered.

Table 2. Nominal damage and equivalent level of damage thresholds

<table>
<thead>
<tr>
<th>Damage level</th>
<th>Thresholds of equivalent level of damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Null</td>
<td>damage = 0</td>
</tr>
<tr>
<td>Light</td>
<td>0 &lt; damage ≤ 5%</td>
</tr>
<tr>
<td>Moderate</td>
<td>5% &lt; damage ≤ 30%</td>
</tr>
<tr>
<td>Severe</td>
<td>30% &lt; damage ≤ 60%</td>
</tr>
<tr>
<td>Total</td>
<td>60% &lt; damage ≤ 100%</td>
</tr>
</tbody>
</table>

Figure 8 shows that the most critical case for a building is when both characteristics, first soft story, and corner asymmetry, are present with high values of each pathology. The results are based on the statistics of the 2017 earthquake, considered the level of damage as showed in Table 2.
As shown in Figure 9, buildings with high-intensity levels of both pathologies presented a considerable loss on average, 31.7% (Reinoso et al., 2021). Almost one out of three buildings had total damage if they had both, a high first soft-story effect and a high corner effect. These statistics clearly show that any mitigation strategy must consider the radical solution or retrofitting these two pathologies. Although structures in the area of study that have these two pathologies are very few (see Figure 9), both were present in most of the collapsed and severe damage buildings. This is extremely important to be pointed out since it will determine what kind of structures should be prioritized in risk mitigation plans.
Structural type vulnerability

Following the same statistics within the case-study zone (Reinoso et al. 2021), the damage curves of four structural type systems that were the most common in the zone-study were estimated: a) flat slabs, b) RC frames, 4) dual systems, and 5) steel frames. The analysis was limited to 63 buildings between seven and nine stories with similar characteristics to the collapsed building located in Alvaro Obregón 286 and that were close to the same accelerometric record CI05 and where site effects are expected to be very similar.

As established in Reinoso et al. 2021, the damage curves were constructed through a hybrid methodology (Kappos, 2016) that models the structural behavior at intensities lower than the acceleration-band where damage was reported. The approach used for assessing the structural performance was based on the capacity curves methodology (Borzi et al., 2008; Silva et al., 2014; Villar-Vega et al., 2017; Silva, 2019), considering the entire universe of buildings in the study area.

Figure 10 shows the damage curves for the four structural types. Likewise, each symbol corresponds to a structural type and the number above each symbol to the number of buildings that showed each damage level for that particular structural type. The gray band shows the accelerations demanded by these structures (which depends on the structural type) obtained with the spectra of station CI05.

Figure 10. Comparison of damage levels of the four structural types studied and the damage curves computed considering all structures in the area of study (Reinoso et al., 2021)

As shown in Figure 10, most of the structures suffered only light or moderate damage (55 structures), six had severe damage and two collapsed. The buildings with severe damage were RC frames and flat slabs, while the collapses occurred in flat slab buildings. The most vulnerable structural system was by far flat slabs, while less vulnerable systems were steel frames and dual systems.
Analysis of the influence of the structural pathologies on the damage

As mentioned before, the flat slab system was the most vulnerable structural type during the 2017 earthquake (and also during the 1985 earthquake). However, not all the buildings with this structural system had severe damage. To understand the structural performance of the seventeen buildings with flat slab in the case-study zone, seven pathologies were analyzed: a) corner asymmetry, b) plan irregularity, c) irregularity in elevation, d) pounding, e) soft story, f) short column effect and g) previous damage.

Figure 11 shows the damage curves for the flat slab buildings with the influence of structural pathologies. The number above each building sketch indicates the number of pathologies found in that flat slab building. The statistics were obtained from Reinoso et al. (2021). These damage curves were calibrated with the average damage for each of the existing pathology intervals (i.e., > 4) and following a similar methodology explained in Figure 10.

Figure 11. Damage levels for buildings with a flat slab structural system, according to the number of pathologies presented (Reinoso et al., 2021)

The structural type is critical for the damage assessment of a building, as shown in Figure 10. However, using this structural characteristic is not enough to describe the building behavior. As shown in Figure 11, the damage level increases considerably with the number and type of structural pathologies. From this figure, when a building has more than three pathologies, the severe damage increases considerably. A proper estimation of building damage must consider the structural type and pathologies that aggravate the structural performance.

Using the machine learning techniques explained above, the corner effect and first soft story were included within the building database used for risk analysis.
Proposed methodology to identify buildings with high risk

This work's main objective is to identify the buildings located in the lakebed zone of Mexico City with a higher seismic risk, considering the main characteristics of the structure such as structural system, year of construction, number of stories, occupancy, and location. Besides, it was necessary to include pathologies that aggravate the structures' vulnerability, such as first soft story, and corner asymmetry that are critical on structural damage according to statistics of 2017 earthquake presented by Reinoso et al. 2021.

Due to the large amplification and soil response variability in Mexico City, it is also necessary to consider the interaction between the periods of the soil and the structure and the characteristics of earthquakes. The methodology used here was divided into two general stages, Preliminary and Diagnosis Stages.

The preliminary stage is focused on the analysis, improvement and optimization of the buildings database for the lakebed zone of Mexico City. Given the uncertainties, it is necessary to use tools such as Geomatic or machine learning. The number of buildings in the original database was reduced, focusing only on housing buildings taller than four stories (40,921 buildings) considering that housing buildings with less than three stories are not vulnerable at all. The methodology for this stage is shown in Figure 12.

Figure 12. Preliminary stage for the proposed methodology.

From the reliable and complete buildings database obtained in the Preliminary Stage, it was possible to perform a risk analysis, using the software R-PLUS (ERN, 2020), so that it is possible to identify buildings with higher risk and prioritize them for any retrofitting program. The Diagnosis Stage steps are shown in Figure 13.
Results

List of buildings with high risk

Figure 15 shows the location of buildings with high risk that should be intervened with priority. The results obtained in each stage of the methodology proposed for identifying vulnerable buildings are shown with different colors. The buildings in red correspond to 264 buildings with priority attention for their intervention. Besides, actual photos of high-risk priority buildings are shown. It is not possible to share the complete and detailed list of buildings with high risk, since the results are confidential and handled by the Mexico City government.

As shown in Figure 14, the estimated damage concentrated in zones with a dominant soil period around $T_g=2.0s$ matches with the area where historically severe damage has been reported. This is because the interaction between the dominant soil period and the natural period of buildings is critical in the seismic analysis, especially in Mexico City's lakebed zone.

From the list of 2,126 buildings obtained in the first step of the Diagnosis Stage, and based on the statistics of damage to buildings caused by historical earthquakes, the buildings were classified starting with what should be urgently intervened due to their high risk. The main characteristics considered to classify structures with high risk were:

A. Year of construction
B. First soft story
C. Corner asymmetry.

In addition to its structural system and location in the city, these three conditions could significantly increase buildings' vulnerability. This decision was based not only on modeling results but also on statistics of damage from historical earthquakes (predominantly 1985 and 2017). The year of construction is also critical due to two main reasons: a) Buildings built before 1985 consider lower seismic demands because they were built with old standards, and b) the cumulative damage to which they have been exposed after two major earthquakes and several intense ones (Quinde and Reinoso, 2020)
Figure 14. Location of the buildings analyzed at each stage of the project.

Figure 15 shows the statistics of the 2,126 buildings obtained from the second filter of the previous phase, considering pathologies and year of construction. As can be seen in Figure 15, most of the high-risk buildings were built before 1985, with first soft story and corner asymmetry.
It should be mentioned that this final list of about 260 buildings does not correspond to all the most vulnerable buildings in the city, since it is practically impossible to reduce the uncertainty regarding the hazard and structural vulnerability. However, the buildings detected correspond to buildings with a high risk of structural damage during future earthquakes, and that should be further analyzed with high priority.

**An overview of housing infrastructure and public policy in Mexico City**

Since the second half of the last century, the catastrophic consequences in terms of life and economic losses due to earthquakes have been documented worldwide. According to the UN, earthquakes are the number one cause of mortality due to natural hazards (721,000 victims, 58%). Therefore, numerous institutions, universities and private and governmental entities have taken initiatives and proposed solutions to attenuate the effect and impact of earthquakes. Although most of these initiatives have created state-of-the-art building standards, codes and practices, they have been developed for new buildings and infrastructure, and rarely they consider the safety of existing buildings. Millions of buildings in many cities in the world have been there for decades, withstanding strong earthquakes but, probably, they are not strong enough and have been considerably weakened, during past strong shakings.

The current project is part of an effort to assess the seismic risk of more than two million buildings in Mexico City to provide knowledge and tools for decision-making and, therefore, to increase the city’s resilience. It is necessary to include not only traditional technical and government participants, but also women, children, young people, poor people, indigenous groups, elderly, migrants and handicapped to create the right policies, plans and codes.

The first goal is to include, for the worst 260 buildings with the highest seismic risk, public policies at the neighborhood, municipality, and state levels, that regulate the maintenance and retrofit of these buildings. These policies must include, in some cases, financially sound policies that may consider demolishing and reconstruction.

To create these public policies, it must be considered five dimensions of the disaster risk for all housing buildings that have accumulated damage during so many strong earthquakes:

1) the number of people living in the asset that will potentially be affected.
2) the vulnerability of the building, assessed with well-known structural engineering knowledge.
3) Human, financial, and technical resources.
4) Hazard intensity and frequency.
5) The available frameworks, such as the Sendai Framework for Disaster Risk Reduction (2015).

To achieve this, the technical professionals assessing the risk should communicate and share the results efficiently with all other participants, such as the government at all levels, the public, local communities, ONGs and the private sector.

At this moment, these ideas are being included in the civil rights policies called DESCA (acronym in Spanish for Economic, Social, Cultural and Climate Rights), where the Mexico City government has the obligation of warranting, with policies of no discrimination, rights such as housing, health and education. However, Covid-19 has put a strong stop in its implementation, and some more months are needed to fulfil this goal.
References


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