

# Vulnerability curves for geotechnical risks evaluation in Mexico City

Curvas de vulnerabilidad para la evaluación de riesgos geotécnicos en la Ciudad de México.

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**ABSTRACT.** In Mexico City, several risk factors for structures have been evidenced, such as regional subsidence, soil cracking, natural and anthropogenic anomalies, which can lead to bad behavior, damage and even cause failure. Additionally, seismic activity has left visible evidence of damage in buildings, infrastructure, and historical monuments. In this paper, a methodology for the evaluation of the vulnerability of foundations that considers geotechnical risks is presented. For this purpose, several research campaigns about foundations and their behavior were carried out. With this information, a database was built. Likewise, a statistical analysis was applied to define the aggravating variables and develop a methodology that allows defining a vulnerability index of building's foundations. With the results obtained, the foundation is located geographically on a map considering its level of vulnerability. In addition, the vulnerability index can be related to the probability of damage to define vulnerability curves. Using the database and taking each of the geotechnical risks as a reference, a methodology is proposed for the construction of foundation vulnerability curves that can be used for risk and reliability analysis. Finally, conclusions are presented.

**KEYWORDS:** Foundations, Vulnerability, Geotechnical Risk. Mexico City.

## 1 INTRODUCTION

In the subsoil of the Valley of Mexico several risk factors for infrastructure, such as regional subsidence, cracking and anomalies (natural and anthropomorphic) have been identified, which can induce damage and even cause the failure of the foundations. Moreover, historical seismic events have left damage to a considerable number of buildings.

To consider properly the risk scenarios, it is necessary to develop and implement prevention programs. Specialists have been working on the development of preventive tools against extraordinary events; as a result, vulnerability assessment methodologies were defined for buildings against different natural hazards (earthquakes, floods, among others). While many vulnerability level estimation methods have been presented in the literature, most of them focus on structures. Therefore, in this work, a methodology is described to include the geotechnical variables that impact the foundations. Furthermore, vulnerability curves are developed according to the observed behavior of the foundations in Mexico City in the context of geotechnical risks.

### 1.1 Simplified methodology

For the vulnerability determination, the next steps will be applied.

- Investigation of subsoil geotechnical conditions.
- Compilation, processing and capture of data about the foundations used in Mexico City.
- Development of a database of the buildings collected and integrated into a Geographic Information System (GIS).
- Classification of buildings according to the vulnerability of their foundation following criteria like those adopted to evaluate the vulnerability of structures.
- Definition of criteria for the selection of which buildings could be analyzed with the methodology.
- Proposal of an analysis methodology that can be applied to a large number of cases, to identify the ones with higher risk.

- Application of the proposed methodology in order to exemplify its use.
- Development of vulnerability curves.

## 2 GEOTECHNICAL CONDITIONS OF MEXICO CITY

The soils of the Valley of Mexico are characterized by their heterogeneity, ranging from high compressibility and low resistance materials in the lake and transition zone, to resistant materials in the hill zone. The regional subsidence present in the lake and alluvial-lacustrine areas of the city is an important source of risks, that manifests itself in damage to service networks and buildings. Furthermore, the existence of geotechnical anomalies originated by natural phenomenon or human activity are a constant source of risks, inadequate behavior and structural problems.

To evaluate the vulnerability of foundations, it is important to identify the features of the subsoil which are capable of inducing bad behavior. The investigation about these anomalies has been carried out by various institutions. For this work, the publication "The subsoil of Mexico City, volume III" (Auvinet *et al.*, 2017) is taken as a reference. The geotechnical risks considered are described below.

### 2.1 Geotechnical anomalies

Based on the historical information contained in old maps and papers, data were obtained about:

- Tlateles (land island), dikes and old roads.
- Chinampas (floating gardens).
- Channels.
- Alluvial and marsh deposits.
- Abandoned foundations.

### 2.2 Regional subsidence

The regional subsidence related to deep pumping of water is the main cause of differential settlements in buildings. Much of the problems of soil cracking that occur in different places of Mexico

City (*Iztapalapa, Tláhuac, Xochimilco and Milpa Alta*), and which have worsened with the 2017 earthquakes, are also a consequence of subsidence.

Regional subsidence affects foundations and underground structures. There are numerous constructions founded on deep foundation (piles) supported by the first hard layer, which seems to protrude from the surrounding terrain due to the consolidation of the upper clay formation. For this work, the map published by the Geoinformatics Laboratory of UNAM is considered to estimate the rate of subsidence (Juárez *et al.*, 2022).

### 2.3 Cracking

Soil cracking has different causes: contraction of clays, tensile and shear stresses produced by the weight of buildings, hydraulic fracturing in flooding zones, seismic movements and cracking associated to regional subsidence in abrupt transition zones (Auvinet *et al.*, 2019). The most destructive cracks are a direct consequence of subsidence.

The cracks identified by the Geoinformatics laboratory were taken as reference for the elaboration of this paper.

### 2.4 Foundations in Mexico City

The design and behavior of foundations in Mexico City has been the subject of numerous researches works over the years (Mendoza, 2007). The options to choose the foundation of a building depends on several geometric and functional characteristics. The most common foundation solutions are:

- Shallow foundations, masonry or concrete footings.
- Reinforced concrete foundation slabs.
- Compensated, partially compensated or overcompensated foundation.
- Point bearing piles.
- Friction piles.
- Special solutions, including control piles, interlaced piles, penetrating point piles, inclusions, etc....

The earthquakes that provoked the most damage in Mexico City are those of July 28, 1957, March 14, 1979, September 19, 1985 and September 19, 2017 (Reinoso *et al.*, 2018). Recent earthquakes, such as those in September 1985 and 2017, showed that many structures did not perform as expected under building codes. Research over the years has shown the following:

- Shallow foundations. Foundations conformed by isolated or continuous footings and slabs (which are used in the lake area), are only acceptable for light and small constructions.
- Compensated or "floating" foundations. Slender buildings founded on a partially compensated foundation can be unstable in seismic conditions. In the case of overcompensated foundations, the interaction with regional subsidence can lead to apparent protruding of the caisson that does not stabilize over time.
- Foundations on point bearing piles. This solution may present serious inconveniences, such as apparent protruding with respect to surrounding ground. As a consequence, the foundation slab is no longer in contact with the soil and the structure may sustain damage if its design did not contemplate such condition. Furthermore, the piles lose their lateral confinement at their top section and become vulnerable to overturning moments and shear forces of seismic origin (Auvinet *et al.*, 2016).

- Friction piles. During the seismic events of September 19 and 20, 1985, there was evidence of the vulnerability of mixed foundations with caisson and friction piles (Mendoza, 2007). 13% of buildings ranging from 5 to 15 levels with this type of foundations experienced significant settlements (Auvinet and Rodríguez, 2004) and four buildings presented total failure (Tamez, 2005).
- Control piles. Some systems presented failures due to tension or shear stresses in the loading structure, or large deformations, generally associated with lack of maintenance.

## 3 VULNERABILITY ANALYSIS

To carry out the vulnerability analysis, a methodology is proposed based on that presented by Reinoso *et al.*, 2018 for structures evaluation. It contains phases with different levels of detail in the evaluation. Each stage serves as a filter to obtain a vulnerability index. The proposed analysis stages are the next:

Preliminary stage (Preliminary geotechnical vulnerability index  $I_{VGP}$ ), a quick diagnosis of the building is carried out, identifying geometry, structural and location characteristics.

Stage I (Geotechnical vulnerability index  $I_{VG}$ ) evaluates the performance of the foundation and the presence of geotechnical hazards.

Stage II (Detailed Analysis), a detailed analysis of the building is carried out, verifying compliance with the current regulation.

The hypothesis test is based on an inverse analysis, in which the conditions that lead to the failure of a foundation are known; then, aggravating factors are determined. A rating is assigned for each factor to calculate the Vulnerability Index. It should be kept in mind that most practical reliability analysis methods contain approximations, even if one or more steps are exact (Baecher and Christian, 2003).

### 3.1 Vulnerability Index

The vulnerability index,  $I_v$ , is characterized by the structural state of a building, it is defined as the combination of vertical and horizontal elements, walls, foundation, among others. There are several methodologies to define the  $I_v$  based on the evaluation of specific parameters. After September 2017 earthquake, several researches related to the topic were carried out. In this work, the conceptual approach proposed for structural evaluation is used (Reinoso *et al.*, 2018). To calculate the score for each variable the next activities were done:

- Choose an analytical model.
- Statistically estimate the influence of the parameters.
- Calculate the statistical moments of a performance function.
- Calculate the vulnerability index.

The workflow for the analysis begins with the collection of information (database conformation); the next activity is locating the data geographically. Additionally, a selection criterion is established to regroup the study cases. The corresponding statistical analysis is carried out to obtain the ratings of each factor, the information obtained generates a new database that includes only the results of the aggravating factors.

To calibrate the rating of each aggravating factor, worksheets were prepared with the parameters required to obtain the  $I_{VG}$  in each stage. Finally, for the validation of the rates obtained, the

methodology was applied to cases that were not considered in the first approach. Each of the analysis Stages and their corresponding factors will be described below.

### 3.2 Preliminary Stage

The preliminary stage  $I_{VPG}$  identifies geometric and structural characteristics and location of the building. An on-site inspection is suggested, but can also be done virtually using software such as Google Maps or Google Earth. It is very similar to the structural review, since the parameters that are collected are the same, the difference lies in the relevant aspects for the foundation. Each variable will be described below.

The first step is name and location the building. Afterwards, each aggravating variable is reviewed according to a criterion (described below), selecting the corresponding scenario, table 1.

Table 1. Aggravating variables criterium to estimate  $I_{VPG}$ .

Aggravating variable	a	b	c
Number of floors	0.0	0.25	0.5
Architectural form	0.0	0.5	1.0
Arch. empty spaces	0.0	0.5	1.0
Vertical modification	0.0	0.5	1.0
Slenderness	0.0	0.5	1.0
Adjacent distance	0.0	0.25	0.5
Verticality	0.0	0.5	2.0
Columns and walls damage	0.0	0.5	2.0
Building age	0.0	0.25	0.5
Structural system	0.0	0.5	1.5
Foundation (Table 2)			
Basement	0.0	0.25	0.5
Geotechnical zone	0.0	1.0	2.0

**Number of floors.** Same criteria as in the structural review, it is considered that buildings with up to three floors do not have significant damage, as do as those with more than 20 floors. It has been observed that the most vulnerable structures have intermediate height. The number of floors begins from the sidewalk level, from that level down the geotechnical factors will be considered.

- 0 - 3 floors.
- More than 20 floors.
- From 4 to 20 floors.

**Architectural.** The evaluation is carried out based on the following criteria:

- Regular, regular rectangles that satisfy the relation  $L \leq 2.5B$ .
- Irregular, polygons that satisfy the relation  $2.5B < L \leq 4B$ .
- Very irregular, "Y", "H", "L" geometric shape different from those mentioned above,  $L > 4B$ .

**Arch. empty spaces.** Same criteria as in the structural review.

- Regular, if the empty spaces are less than 20% of the plant area.
- Irregular, empty spaces between 20% to 50%
- Very irregular, more than 50% of the plant area.

**Vertical modification.** The geometric variation is not present only in plan designs; it can also correspond to reduction or expansion of the area as the height increases. The criteria are similar as for the structural review, however, in the case of foundations, the slenderness will be reviewed in another section.

- Regular, the plant area increases or reduces 10%.
- Irregular, the plant area increases or reduces 10% to 30%.

- Very irregular, the plant area increases or reduces >30%.

**Slenderness.** Foundations based on footings, slabs and caissons are reactive to the slenderness ratio. Slenderness is frequently associated to differential settlement or notable collapses. Considering the impact that this parameter has on the foundation, it is required to have a specific variable within the analysis to determine this characteristic.

- Low, height/shortest side,  $H/B < 2$ .
- Medium, if the next relation occurs  $2 \leq H/B < 4$ .
- High, if the relation is  $H/B > 4$ .

**Adjacent distance.** The absence of space in the boundaries between buildings can cause knocking between them during earthquakes. The regulation establishes in its earthquake design standards that every building must guarantee a minimum distance, S, at its boundaries of 3cm per floor.

- Same or more than standard,  $S \geq S_{min}$ .
- Less than standard,  $S < S_{min}$ .
- No distance exists,  $S = 0$ .

**Verticality.** The high compressibility of the CDMX subsoil can cause considerable deformations over time that induce poor behavior if they are concentrated in one point. The standards consider that risk exists for the structural behavior when its value exceeds 1%, calculated as the relation between the lateral displacement ( $\Delta$ ) with respect to the height of the building (H).

- No evidence.
- $\Delta/H < 1\%$ .
- $\Delta/H \geq 1\%$ .

**Columns and walls damage.** Same criteria as in the structural review (Reinoso *et al.*, 2018); The building is checked for evidence of cracks in structural elements; Damage in surfaces or coatings are not considered. The damage condition is selected based on the crack width, AG.

- Without evidence.
- AG, 0.3mm to 1mm.
- AG more than 1mm.

If there has been evidence of damage at any time during the useful life of the building, it must be reported.

**Building age.** The construction year is related to the structural capacity to resist seismic actions; it also allows to have an idea of the design criteria that were adopted for its construction (regulations).

- After 1987.
- Between 1956 and 1986.
- Before 1956.

**Structural system.** The structural system will be chosen based on the groups defined in the methodology for structures reviews (Reynoso *et al.*, 2018), three groups are considered.

- Masonry and rigid buildings.
- Systems based on frames (reinforced concrete or steel).
- Concrete columns and slabs.

**Foundation.** Based on the data collected about the most used foundations in CDMX and the behavior observed in different research works, one analysis was executed to assign a qualification for the estimation of the vulnerability index.

The criteria for the calculation of  $I_{VPG}$  are presented in Table 2.

Table 2. Criteria to estimate  $I_{VG}$ , depending on the foundation.

Foundation	Value
Shallow foundation	0.25
Compensated foundation	1.0
Foundations on point bearing piles	0.5
Friction piles	0.5
Penetrating piles	0.5
Control piles	0.25
Special foundations	0.25

**Basement.** In a similar way to the number of floors, the sidewalk level is taken as a reference for counting the number of basements according to the following classification:

- Without evidence.
- Less than the number of floors.
- Greater than the number of floors.

**Geotechnical zone.** The distribution of subsoil materials in CDMX has been studied and employed to define a geotechnical zoning in the construction code. To evaluate  $I_{VG}$ , the zoning established in the standard is used:

- Zone I, Foothill.
- Zone II, Transition.
- Zone III, Lake.

### 3.3 Stage I

In this stage, the behavior of the foundation is reviewed, and the presence of any of the described geotechnical risks is verified, including regional subsidence, geotechnical anomalies and cracking. To assess the geotechnical environment, the developed Geographic Information System (GIS) is used. This phase helps to identify buildings whose behavior is not appropriate; it is recommended to conduct a structural evaluation to gain a comprehensive overview of the building. Similarly to the Preliminary Phase, aggravating factors are assessed by identifying the corresponding condition to obtain the  $I_{VG}$ , as shown in Table 3.

Table 3. Aggravating variables criterium to estimate  $I_{VG}$ .

Aggravating variable	a	b	c
Settlement	0.0	0.5	1.0
Apparent protruding	0.0	0.5	1.0
Subsidence rate	(table 4)		
Cracking	0.0	0.25	1.0
Surface deformations	0.0	0.25	0.5
Geotechnical anomalies			
Geological	0.0	0.2	
Pre-Hispanic	0.0	0.2	
Chinampas	0.0	0.2	
Channels	0.0	0.2	
Foundation abandoned	0.0	0.2	
Engineering level	(table 5)		

The aggravating factors and the proposed criteria to be considered are described below.

**Settlement.** Differential settlement in a building may occur without necessarily indicating poor behavior. To determine whether settlement has occurred, a site visit and visual inspection are recommended. Although assessing the magnitude of settlement can be subjective, it is important to carefully document this behavior.

- Without evidence, no settlements are observed.

- Moderate, settlement exists but is lower than that considered in the design in accordance with the standards; It is important that it be noted for periodic monitoring.

- Significantly. The building settlement is clearly visible.

**Apparent protruding.** Protruding of the foundation can be easily detected by performing a visual inspection; The proposed criterion for this condition is similar to that used in the evaluation of the settlement.

- Without evidence.
- Moderate, it is possible to see a different level between the surrounding land and the building; It is important that it be noted for periodic monitoring.
- Significantly. the building protruding is clearly visible.

**Subsidence rate.** Regional subsidence impacts foundations and infrastructure, resulting in differential settlements and/or apparent protruding. The rate at which it occurs varies. To determine the rate of subsidence, the map provided by Juarez *et al.* (2022) was consulted. Based on this data, the criteria are outlined in Table 4.

Table 4 Criteria to estimate  $I_{VG}$ , depending on subsidence rate.

Subsidence rate	Value
No evidence	0.0
0 – 5 cm/year	0.2
5 – 10 cm/year	0.3
10 – 15 cm/year	0.4
15 – 20 cm/year	0.5
20 – 25 cm/year	0.6
25 – 30 cm/year	0.7
30 – 35 cm/year	0.8
35 – 40 cm/year	0.9
40 – 45 cm/year	1.0

**Cracking.** Potential cracking zones within the city have been identified in the GIS. It is recommended to conduct an on-site visual inspection (if possible), or a virtual inspection using photographs, to accurately identify and document the development of the crack. Once the crack is confirmed, the following criteria are proposed:

- Without evidence.
- Proximity of the crack, if the crack is visible on the pavement or public roadway, it may extend to the building and cause damage. It must be identified to monitor its progression and to define appropriate preventive measures.
- Significant subsoil cracking, the evidence of the crack and the damage it causes are clearly visible.

**Surface deformations.** The compressibility of lake deposits is evident, as deformations are observed in sidewalks, streets, and in long buildings. A virtual or physical inspection should be conducted, with careful attention paid to the surroundings to identify these behaviors.

- Without evidence.
- Moderate, exists; It is possible to see some deformation in the surrounding land and the building.
- Remarkable. the deformation in the floor and sometimes in the building is easily perceived.

**Geotechnical anomalies.** In previous sections, the existence of geological and pre-Hispanic structures embedded in the subsoil was highlighted; these induce improper behavior in foundations as they represent a point of greater rigidity.

However, the presence of the anomaly will not necessarily result in poor performance, but it is still important to document it in order

to monitor the building. Therefore, the assessment is based on whether the anomaly exists (b) or not (a). To identify geotechnical anomalies, GIS (Geographic Information System) is used.

**Engineering level.** The performance of a building is influenced by the design and the execution of work on-site. In 1985, Lambe and his colleagues introduced a framework for analyzing earthworks, demonstrating that the design Safety Factor (FS) is primarily relevant within the context of the analysis, as its effectiveness greatly depends on the construction, supervision, and maintenance of the project. Consequently, four engineering levels were established. These suggest that even with a high FS value, if comprehensive studies, adequate construction control, and a regular preventive maintenance program are not implemented, the actual FS will be lower than what was initially calculated during the design phase.

To effectively evaluate each of the factors described, it is ideal to have comprehensive information about the building. However, access to calculation reports, construction documents, as-built plans, and other records is not always possible. It is advisable to request the construction history from the building's managers or representatives to compile a building dossier. This section aims to identify the engineering level at which the project was executed. Table 5 outlines the considered engineering levels.

Table 5. Engineering level criterium to estimate  $I_{VG}$ .

	Design	Construction	Performance	$I_{VG}$
I	Measured data, complete assessment for design	Full time supervision	Continuous inspection and maintenance	0.0
II	Measured data on site, assessment with omissions in design	Part time supervision	Periodic inspection	0.3
III	Approximate design	Informal supervision	Annual inspection	0.5
IV	No rational design	No supervision	Occasional inspection	1.0

### 3.4 Stage II

In this stage, an analysis requiring specialized technical expertise is necessary. It is only conducted if the  $I_{VG}$  value exceeds a specific threshold, which will be detailed later in this document. The objective is to develop an appropriate remediation or rehabilitation strategy. Comprehensive and updated information including geometry, structural details, construction materials, architectural layout, and time-sequenced photographs must be collected.

Due to the complexity of the analysis, it should be performed by specialists to accurately assess the extent of the damage and the actual behavior of the structure. The properties of the materials and the structural integrity can be evaluated through both destructive and non-destructive testing, as well as building load tests. If an anomaly is detected during the vulnerability assessment, it can be confirmed through direct or indirect site exploration. This approach is also useful for determining the depth of displacement and assessing the integrity of the foundational components. Compliance with current regulations must be verified. It is advisable that, following any intervention on the property, the results of these analyses be integrated back into the database along with the conclusions drawn, to enhance the evaluation model.

### 3.5 Vulnerability level

The methodology outlined in the preceding sections has been meticulously crafted to assess a substantial number of buildings and to delineate a risk scenario. Each stage of the analytical process functions as a sieve, pinpointing buildings that exhibit pronounced vulnerability. This systematic review facilitates the timely identification of structures requiring urgent intervention. To systematically categorize each building, precise vulnerability criteria have been established, which are presented in Table 6.

Table 6. Vulnerability classification levels.

Range	Vulnerability Level	Recommendation
$0 < I_{VG} < 4$	Slight	It does not need intervention or additional actions
$4 \leq I_{VG} < 7$	Moderate	Periodic monitoring and preventive maintenance
$I_{VG} > 7$	Severe	Perform detailed analysis, determine correction and mitigation measures

Dynamic changes in vulnerability and hazard agents indicate that risk is inherently non-static; it evolves over time. These temporal variations must be meticulously accounted for when conducting specific assessments, whether implementing corrective interventions (addressing current risk) or prospective interventions (anticipating future risk).

## 4 DEVELOPMENT OF VULNERABILITY CURVES

Vulnerability curves constitute mathematical models that estimate the probability of damage to buildings under specific threats. These models are formulated by rigorously analyzing observed damage data while considering structural characteristics, geometrical configurations, construction quality, and observed behavior. Such models are instrumental for risk assessment, strategic planning, and risk management (Abbas *et al.*, 2013).

Accurate and detailed information regarding the materials, geometric configuration, structural system, number of floors, and location is crucial. Regrettably, such information is often incomplete or unavailable. Vulnerability curves typically function to delineate the correlation between probable damage values. Initially developed for quantifying seismic risk, the application of vulnerability functions has now extended to various fields, including industrial, economic, and social sectors, proving to be an effective method for assessing urban vulnerability.

The applicability of these curves varies significantly across different regions or localities due to distinct threat profiles; thus, vulnerability curves derived from other studies may not be universally applicable where similar phenomena occur. Site-specific studies are essential for accurate vulnerability assessment. For instance, San-Guy Yun *et al.* (2021) have outlined a methodology for constructing curves from empirical observations, focusing on wind intensity. Similarly, Saeidi *et al.* (2009) investigated land subsidence associated with underground mining activities.

Vulnerability curves are prepared based on the identified aggravating factors, evaluating their influence on the frequency and behavior of events. This methodology allows us to estimate the potential damage to buildings that are grouped according to one of the selected criteria. The generation of these curves mainly requires

the following input data, such as damage scale, building typology and intensity criteria. An exhaustive review was carried out of various methodologies implemented in other cities around the world, which face similar hazards to those observed in Mexico City. The steps for preparing vulnerability curves can be summarized in a simplified manner as:

- Define a criterion for evaluating vulnerability (intensity)
- Establish a building typology.
- Select the risk to evaluate and its magnitude.
- Establish a methodology for evaluating damage or vulnerability.
- Simulate probable configurations based on building type.
- Evaluate the level of damage or vulnerability for each case.
- Calculate the probability of exceedance for each damage category.
- Calculate the average of the recorded damage.
- Graph each point obtained for each magnitude of the evaluated risk.

It is possible to develop empirical vulnerability curves based on historical damage data by categorizing this data according to construction types, materials, load-bearing capacities, and other relevant factors. These curves can be integrated with construction typologies, such as geometry, structure type and foundation. The vulnerability index, derived from applying this methodology, serves to quantify potential damage levels in response to specific threats. This quantification is based on variables that characterize the behavior of the system. To facilitate the construction of these curves, databases have been built to gather the necessary information.

#### 4.1 Development of a buildings database

Compiling detailed records on the architectural, geometric, and structural characteristics of every building within the city represents a substantial and complex task. Architectural designs, material compositions, and structural frameworks vary significantly among constructions. The database, which has been established and is continuously being expanded, enables an evaluation of the efficacy of the assessment methodology introduced in the initial phase of this research. An ongoing data collection campaign seeks to augment this database, targeting conference proceedings, technical articles, theses, and reports as primary sources.

Although these sources are publicly accessible, they do not always provide adequate detail for comprehensive analysis. To discern pertinent data from the non-essential, specific selection criteria have been applied, including geotechnical zoning, property usage, availability of information, and distinctive features.

The database facilitates a comprehensive analysis of the foundation systems employed in CDMX, elucidating the current conditions and identifying those with inappropriate performance. This analysis enables the identification of variables that contribute to increased vulnerability. Initially, a review of 500 documented cases was conducted; however, not all cases met the predefined criteria. Consequently, a subset of 150 projects was selected for further analysis. Additionally, the integration of 7,408 Geo-Structural reports, prepared by the *Commission for the Reconstruction of Mexico City*, enriched the database. Consequently, the database encompasses a total of 7,561 cases that adhere to the stringent selection criteria. Figure 1 illustrates the

distribution of buildings across various municipal districts based on the compiled data.

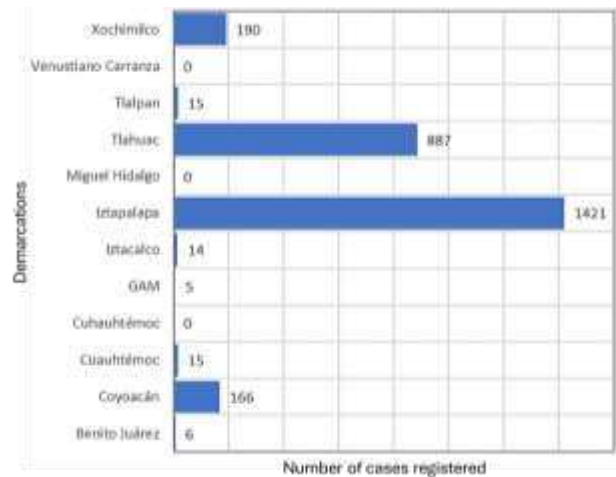


Figure 1. Building statistics in the database.

Once the I<sub>v</sub>G analysis for each building was done, the results are documented for subsequent interpretation. One of the primary benefits of establishing a database is the capability to visualize with graphics the distribution of the different I<sub>v</sub>G parameters.

For instance, utilizing the data in the database, a graph was generated to depict the vulnerability of compensated foundations within different geotechnical zones (Fig. 2). Analysis of the sample indicates that a significant proportion of structures in the lake zone exhibit severe vulnerability.

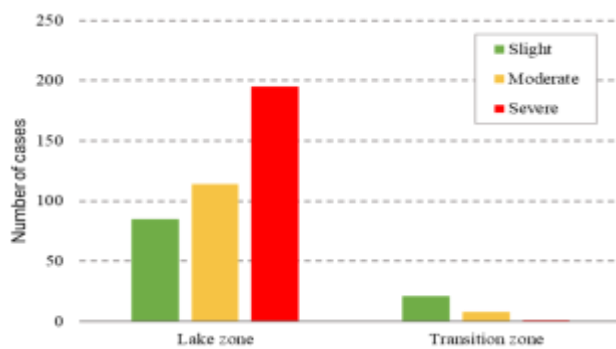


Figure 2. Database statistics based on the geotechnical zone for compensated foundations.

In this study, the factors that degradate the behavior of the foundations were described. A total of 24 variables have been identified, each assigned with a rating based on the condition of the property. These variables are summarized in Tables 1 and 3.

#### 4.2 Development of a simulated building database

To develop the vulnerability curves, two types of analyses were conducted, one utilizing recorded observational data and another based on simulations of theoretical buildings.

Most of the available data corresponds to buildings with 0 to 3 floors and shallow foundations, thus limiting the scope of the study. To account for additional architectural configurations,

theoretical buildings were generated. The variability in the criteria used across different damage assessment methodologies aligns with the architectural typologies considered. Each building's final assessment value is determined using a uniform statistical distribution. However, other typological parameters such as material, foundation type, and structural shape contribute to uncertainties. Consequently, the development of vulnerability functions requires validation through real world observations and in-depth case studies to explore the variability of these components. It is important to note that the resulting curves are predominantly qualitative.

Calculating every potential scenario within the evaluation methodology would yield an impractical figure of 385,698,620,160 cases, a number that vastly exceeds the actual count of buildings in CDMX. Therefore, a more manageable approach was adopted by randomly generating a sample of 100,000 scenarios, specifically focusing on configurations with compensated foundations. During this simulation, the foundation parameter was held constant while omitting variables affected by geotechnical anomalies and cracking. Buildings exceeding 20 floors were also excluded. This approach facilitated the random generation of virtual buildings for analyzing data distribution, vulnerability variability, and the development of vulnerability curves.

### 4.3 Development of vulnerability curves, cracking

There are 431 buildings in the database (described in section 4.1) that share similar characteristics of geometry, structure and foundation, located in a potential cracking zone. For each building the  $I_{VG}$  is obtained to establish a damage stage. To develop the curve, the probabilities of exceeding certain vulnerability values in terms of a variable chose are calculated. In this example, the engineering level was chosen as a reference variable, which serves as an indicator of compliance with standards. To determine the curves, the probability of damage,  $P(v_i)$ , in each vulnerability category was calculated with the following equation:

$$P(v_i) = N(v_i)/n \quad (1)$$

Where  $N(v_i)$ , is the number of buildings in the damage condition  $v_i$ , and  $n$  is the total number of buildings. These calculations involve estimating a lognormal distribution curve, which is uniquely defined by two parameters, mean  $\mu$  and standard deviation  $\sigma$ , as described by Sang-kun *et al.* (2021).

To optimize the model, the least squares method (MSE) was applied. The resulting vulnerability curve is illustrated in Fig. 3.b. Figure 3.a displays a histogram showing the distribution of observations relative to  $I_{VG}$ . The parameters of the log-normal distribution are derived from Equations 2 and 3, respectively, where  $m$  is the average and  $v$  is the variance. The summary of the parameters is provided in Table 7.

$$\mu = \log(m^2/\sqrt{v+m^2}) \quad (2)$$

$$\sigma = \sqrt{\log(v/m^2 + 1)} \quad (3)$$

Table 7. Log normal parameters.

Parameters	Slight	Moderate	Severe
$\sigma$	0.37044	0.28319	0.23712
$\mu$	1.38411	1.78526	1.93804

Once the parameters are obtained, the cumulative distribution function is obtained by equation 4.

The cumulative distribution is presented in Fig. 3.c.

$$F(x|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^x \frac{1}{x} \exp\left\{-\frac{(\log x - \mu)^2}{2\sigma^2}\right\} dx, > 0 \quad (4)$$

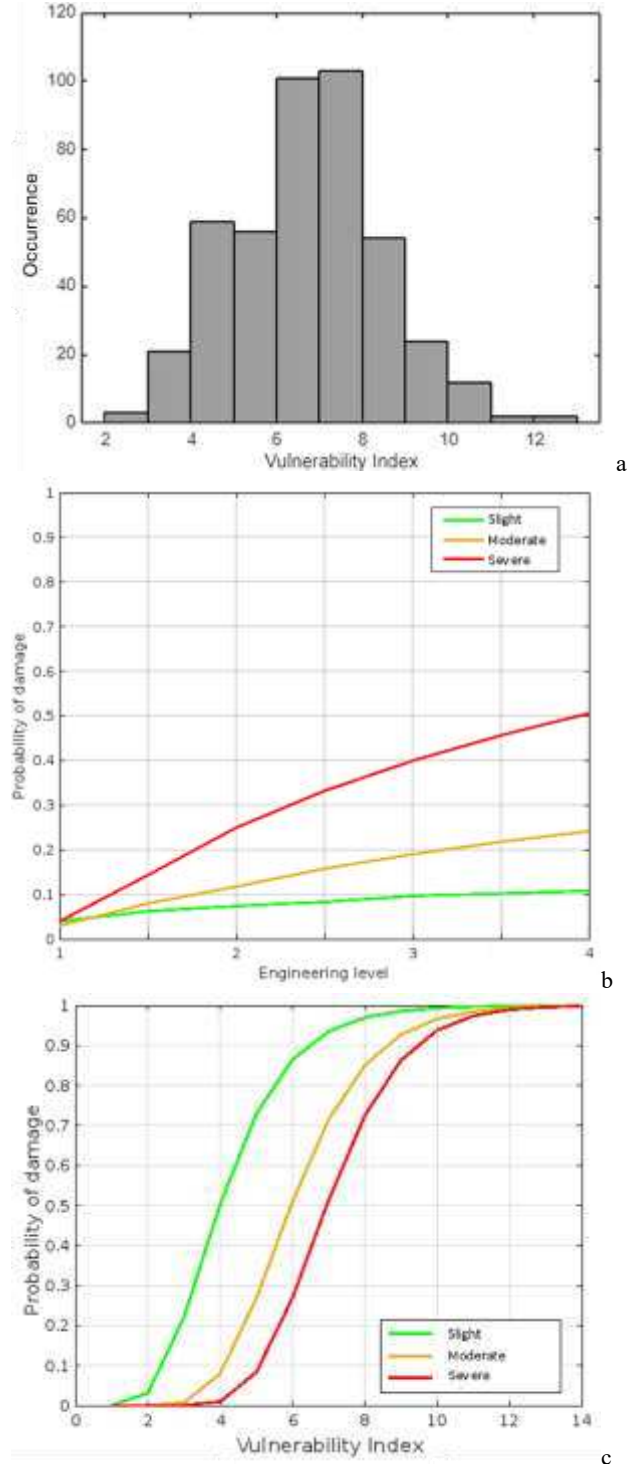


Figure 3. a) Histogram; b) Vulnerability curve; c) Cumulative distribution.

Based on the analysis of this subset of buildings, the following conclusions can be drawn:

- Buildings with Low-Quality Construction. Buildings characterized by poor construction quality, particularly in the structures and foundations, suffer significant damage. Such damage often renders these buildings uninhabitable. When cracks affect these structures, the damage is substantial. The situation worsens during earthquakes, often leading to complete collapse and necessitating either relocation or rebuilding.
- Rigidity of Foundation. The rigidity of a building's foundation contributes to resistance against crack propagation. In some instances, even when a crack visibly crosses a building, the structure remains undamaged and does not reach a state of critical vulnerability.
- Subjective Vulnerability Near Cracks. The vulnerability of buildings situated close to cracks varies and can be considered subjective. In some cases, a crack's trajectory might pass around the perimeter of a building without causing any harm, whereas in other cases, under similar conditions, the impact is significant and noticeable.

The methodology proposed allows to identify and define areas of high vulnerability, whose attention is a priority. Likewise, it is possible to build on maps and position the variation of the vulnerability index based on any variable or geotechnical risk; in parallel, other structural characteristics can be added, an example of this type of control sheets is presented in Figure 4. With the information generated, it is possible to obtain a global and multifactorial overview of the risk scenario.

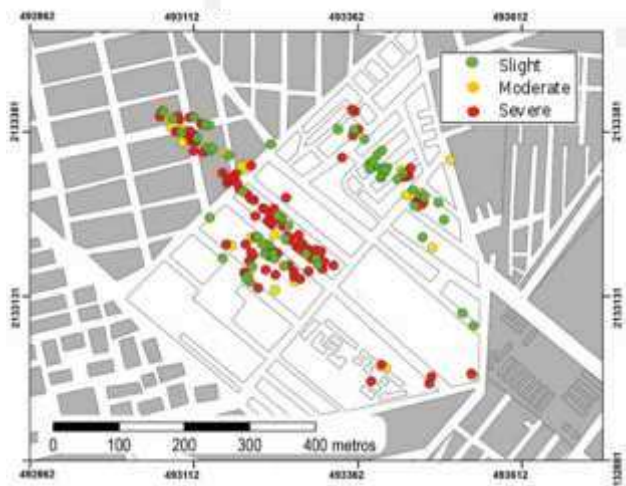


Figure 4. Cracking vulnerability control sheet.

#### 4.4 Development of vulnerability curves, subsidence

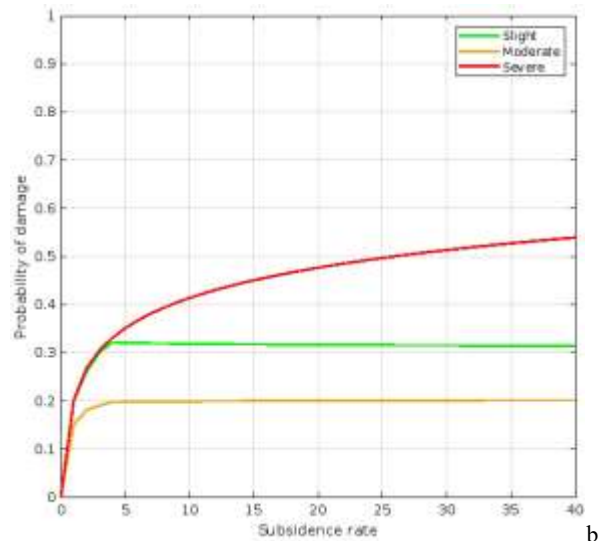
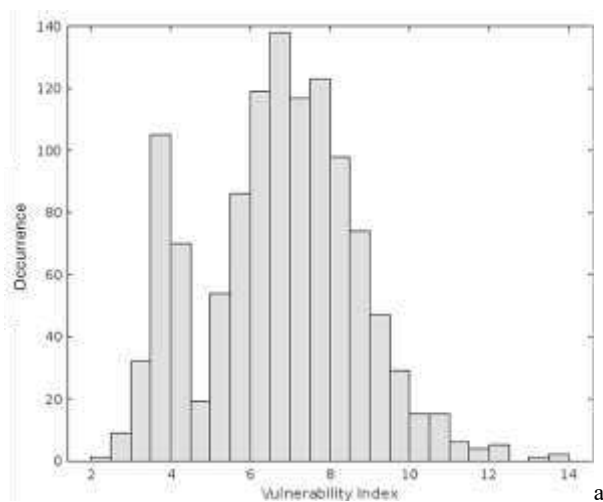
The database primarily focuses on specific areas within Mexico City (CDMX), particularly those severely affected by the September 2017 earthquake. Regrettably, insufficient foundation data hindered the generation of accurate subsidence speed curves. To address this limitation, virtual buildings for approximation were employed. The selection criteria defined were applied to refine the simulated data. Initially, a sample of 68,000 buildings was obtained, plus the cases contained in the database; In total 65,588 cases were meticulously selected to construct the curves.

In order to further filter the information, only buildings whose foundation solution is Compensated were selected. The distribution of cases based on  $I_{VG}$  is depicted in Figure 4.a. In the previous section, the procedure used to obtain the curves was detailed. Once the data is structured, the parameters that characterize its distribution ( $\mu$  and  $\sigma$ ) are calculated, which are shown in Table 8. Next, the necessary adjustment is carried out to obtain the curves, as shown in Figure 5b.

Table 8. Log normal parameters.

Parameters	Slight	Moderate	Severe
$\sigma$	0.10878	0.10061	0.12504
$\mu$	1.28749	1.81342	2.12425

Figure 5.a shows the vulnerability curves based on the variation of the  $I_{VG}$  and the subsidence speed as a fixed variable. The figure presented encompasses the behavior within the database. For this example, the damage probability distribution was generated for the velocity case of 10-15cm/year, Figure 5.c. It is important to mention that each speed has an associated probability distribution for each vulnerability level.



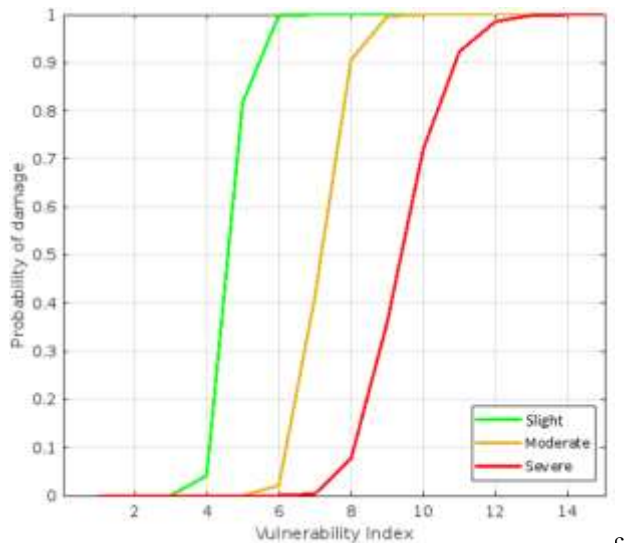


Figure 5. a) Histogram; b) Vulnerability curve; c) Cumulative distribution for 10-15cm/year.

The curves obtained are only indicative, they require a validation process using real data.

## 5 CONCLUSIONS

A bibliography compilation campaign was undertaken in Mexico City to explore the characteristics and behaviors of existing foundations; moreover, a compilation of geotechnical risks prevalent in transition and lake zones was performed. With the information collected the following was achieved:

- Generation of a database of geotechnical information on foundations.
- Implementation of a Geographic Information System for Geotechnical Vulnerability of Foundations (GIS-VGC).
- Definition of a methodology for calculating the "I," index drawing upon the framework established by Reinoso *et al.*, 2018. This involved delineating analysis phases and identifying aggravating variables for each stage.

The selection criteria for this study included geotechnical zoning, building usage, available information, and building characteristics. Statistical analyses were conducted to assign scores to each aggravating factor, defining vulnerability intervals as slight, moderate, and severe.

The proposed methodology offers systematic applicability to other buildings. However, the precision of analyses depends on the quality and quantity of available data, underscoring the importance of planning data collection campaigns.

Furthermore, the methodology for vulnerability analysis holds regional applicability, providing a comprehensive overview of building risk statuses. The resultant insights enable the formulation and refinement of emergency strategies and facilitate the creation of control sheets for identifying vulnerable areas.

Given Mexico City's significant population and housing concentration, proactive prevention programs are imperative. It is advisable to systematically evaluate more buildings, observe recurring aggravating factors, compare results, and recalibrate

proposed values as needed. This iterative process aims to document as many buildings as possible across the city.

## 6 ACKNOWLEDGEMENTS

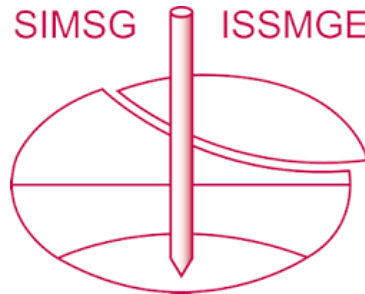
The sponsorship received from Institute for Construction Safety of the Government of Mexico City for the preparation of this research is gratefully acknowledged.

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*The paper was published in the proceedings of the 17th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVII PCSMGE) and was edited by Gonzalo Montalva, Daniel Pollak, Claudio Roman and Luis Valenzuela. The conference was held from November 12<sup>th</sup> to November 16<sup>th</sup> 2024 in Chile.*