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Reliability of building foundations on soft soils

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ABSTRACT: In recent years, evaluating the vulnerability of building foundations on the lacustrine soils of Mexico City has gained importance (Auvinet *et al.*, 2022, 2024). These evaluations consider the geometric and architectural features of buildings (e.g., height, slenderness ratio), their interaction with adjacent structures, structural system, foundation type, building age, visible damage, and degree of deterioration or partial collapse. Geotechnical aspects are also addressed, including settlement measurements, apparent protrusion, surface deformations, and sidewalk or ground displacements near the building. Geotechnical hazard assessments using Geographic Information Systems (GIS) incorporate regional subsidence, subsoil cracking, and geotechnical anomalies. The applied methodology estimates a vulnerability index to quantify damage exposure and the likelihood of inadequate foundation performance. Vulnerability curves complement this assessment but have limitations, as they do not reflect the performance of foundations in terms of soil strength and deformation behavior. To address these gaps, this study combines statistical and deterministic approaches. A Monte Carlo simulation was performed to evaluate the reliability of shallow foundations on soft soils with cracking potential. The resulting fragility curves estimate the probability of structural failure as a function of the limit states established in local regulations.

KEYWORDS: Soft soil, cracking, vulnerability, reliability, foundations.

1 INTRODUCTION

Reliability is defined as the probability that a system will perform its intended function satisfactorily over a specified period and under defined conditions. In geotechnical engineering, reliability analysis estimates the likelihood of failure by evaluating the structural response under uncertainty. This is typically achieved using probabilistic tools and statistical indicators.

In Mexico City, assessing the reliability of shallow foundations is particularly relevant due to the complex geotechnical conditions of the Valley of Mexico. The subsoil exhibits high spatial heterogeneity, transitioning from soft, highly compressible clays in the lacustrine zone to more competent deposits in the hill zone. This stratigraphic complexity, combined with ongoing regional subsidence, poses significant risks to urban infrastructure, including differential settlements, service disruptions, and structural damage.

In addition to stratigraphic variation and subsidence, geotechnical anomalies—both natural and anthropogenic—introduce further uncertainty in foundation performance. These anomalies include altered subsoil zones resulting from ancient canals, pre-Hispanic structures, and historical groundwater extraction, many of which are no longer visible at the surface but remain active underground. Their interaction with regional subsidence has led to widespread cracking phenomena, compromising the integrity of buildings, particularly in transitional areas.

Given this context, understanding and predicting foundation behavior in soft soils is essential not only for new developments but also for evaluating the vulnerability of existing structures. Although various empirical methods exist to estimate damage potential, they often fail to systematically incorporate the interaction between subsoil behavior and foundation performance. For this reason, integrating observational data with probabilistic simulations provides a more robust framework for risk assessment.

The geotechnical anomalies considered in this study draw on the findings of *"The Subsoil of Mexico City, Volume III"* (Auvinet *et al*., 2017), as well as recent investigations on subsoil cracking and regional subsidence. This research aims to bridge the gap between observational vulnerability assessments and simulation-based reliability analysis, ultimately contributing to safer and more resilient urban development in Mexico City.

2 THE MEXICO VALLEY SOFT SUBSOIL

The subsoil of the Mexico Valley presents several risk factors for infrastructure, including regional subsidence, subsoil cracking, and geotechnical anomalies (natural and anthropogenic) that have been documented as causes of structural damage and even foundation failure. To properly account for these risk scenarios, the development and implementation of prevention programs is essential. In recent years, specialists have advanced the creation of preventive tools aimed at mitigating the impact of extraordinary events. As part of these efforts, vulnerability assessment methodologies have been developed to evaluate buildings exposed to various natural hazards, such as earthquakes and floods.

In this study, vulnerability curves were constructed based on the observed behavior of building foundations in Mexico City under geotechnical risk conditions. These curves aim to provide a probabilistic estimation of damage potential in response to subsoil hazards. Additionally, numerical analyses were conducted to support and reinforce existing maintenance and monitoring standards, with the goal of improving long-term infrastructure resilience.

2.1 *Geotechnical anomalies*

Historical information retrieved from old maps and archival documents provided valuable data on the following topics relevant to the geotechnical characterization of Mexico City's subsoil:

- Artificial islands (tlateles), pre-Hispanic dikes, and roads.
- Chinampas (ancient agricultural platforms).
- Hydraulic canal systems.
- Distribution of alluvial and clay deposits.
- Locations of abandoned foundations.

This information was used to identify zones of anthropogenic influence and potential subsurface anomalies that may affect foundation performance.

2.2 *Regional subsidence*

Regional subsidence caused by deep groundwater extraction is the primary driver of differential settlements in buildings across Mexico City. This phenomenon has exacerbated soil cracking in several boroughs, including Iztapalapa, Tláhuac, Xochimilco, and Milpa Alta, particularly following the 2017 earthquakes.

Subsidence not only impacts surface infrastructure but also undermines the integrity of foundations and underground structures. In many regions, deep foundations (e.g., piles) anchored in the first competent layer now appear to protrude above the pavement level. This phenomenon is a consequence of the progressive consolidation of the overlying clay strata.

To better understand this process, the Geocomputing Laboratory of UNAM has developed a subsidence rate map for Mexico City, illustrating annual vertical displacements across the region (Juárez *et al*., 2022).

2.3 *Subsoil cracking*

Subsoil cracking in Mexico City arises from multiple factors, including clay contraction, tensile and shear stresses induced by structural loads, hydraulic fracturing in flood-prone areas, seismic activity, and subsidence-related cracking in abrupt transition zones (Auvinet *et al*., 2023). Among these, the most destructive cracks are directly associated with regional subsidence occurring at sharp geotechnical boundaries between soft clays and stiffer deposits (Auvinet *et al*., 2017).

2.4 *Foundations in the soft soils of Mexico City*

The design and behavior of foundations in Mexico City have been the subject of numerous research studies over the years. The most implemented foundation solutions include:

- 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.

The earthquakes of September 1985 and 2017 revealed that while some structures failed to meet expected performance standards defined by building codes, in most cases the foundations themselves did not exhibit significant damage. Long-term research has yielded the following insights:

Shallow foundations. Isolated or continuous footings and slabs—commonly used in the lacustrine zone—are suitable only for lightweight and low-rise constructions.

Compensated foundations. Slender buildings supported on box-type partially compensated foundations may be unstable under seismic loading. Overcompensated foundations can interact negatively with regional subsidence, leading to apparent upward movement of the foundation (or caisson), whose settlement often does not stabilize over time.

Point-bearing piles. This solution may lead to significant issues, such as apparent protrusion above the surrounding ground due to differential settlement. As a result, the foundation slab can lose contact with the supporting subsoil, and the structure may suffer damage if this condition was not considered in the design. Additionally, piles may lose lateral confinement at their upper sections, making them vulnerable to seismic shear forces and overturning moments.

Friction piles. During the earthquakes of September 19 and 20, 1985, the vulnerability of mixed foundation systems (caisson and friction piles) became evident. According to Mendoza (2007), 13% of buildings with 5 to 15 storeys and this foundation type experienced significant settlements. Four buildings even collapsed entirely (Tamez, 2005; Auvinet and Rodríguez, 2004).

Finally, Control piles systems exhibited failures due to tensile or shear stresses in the superstructure, or large deformations associated with inadequate maintenance over time.

2.5 *Foundations database*

Compiling detailed records of the architectural, geometric, and structural characteristics of every building in Mexico City represents a substantial and complex endeavor. The wide variability in architectural designs, material compositions, and structural systems presents major challenges to achieving a standardized dataset.

To address this, an ongoing data collection campaign has focused on developing a comprehensive database by incorporating information from conference proceedings, technical papers, academic theses, and institutional reports. Although these sources are publicly accessible, they often lack sufficient detail for in-depth geotechnical analysis. To filter and prioritize relevant data, a set of selection criteria was applied, including geotechnical zoning, property use, data availability, and distinctive structural or geotechnical features.

The resulting database facilitates a systematic analysis of foundation systems employed across Mexico City, allowing for the assessment of current performance and the identification of systems exhibiting signs of inadequacy. This, in turn, supports the identification of variables associated with increased vulnerability.

An initial review encompassed 500 documented cases, though it should be noted that not all these cases met the predefined selection criteria. A refined subset of 150 projects was selected for detailed analysis. Furthermore, a total of 7,408 geo-structural reports, which were compiled by the Commission for the Reconstruction of Mexico City, were integrated into the dataset. The final database consists of 7,561 cases that meet the established inclusion parameters.

3 VULNERABILITY INDEX

To perform the vulnerability analysis, a methodology developed by Velasco *et al.* (2022) was applied. This method evaluates different parameters related to the geometry, structural characteristics, and geotechnical conditions of the buildings to obtain a vulnerability index. The analysis consists of three stages:

Preliminary stage (Preliminary geotechnical vulnerability index V_{GP}): a rapid diagnosis based on general building characteristics such as geometry, location, and structural configuration.

Stage I (Geotechnical vulnerability index V_G): Evaluation of the foundation's performance considering geotechnical hazards identified.

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

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 level*

As part of the methodology used to define a vulnerability index, specific safety thresholds were established to classify buildings according to their risk level. These thresholds, summarized in Table 1, allow for the early identification of structures requiring preventive or corrective actions. While slightly vulnerable buildings may not need immediate intervention, those classified as severely vulnerable should undergo structural verification and, if necessary, retrofitting to prevent collapse under geotechnical stress.

One of the key criteria in this evaluation is the proximity of surface cracks to the building footprint, which serves as a basis for constructing vulnerability curves. This systematic approach enhances the timely identification of high-risk structures and supports prioritization in intervention planning.

Table 1. Vulnerability classification levels.

Range	Vulnerability Level	Recommendation
$0 < I_{VG} < 4$	Slight	No need for intervention or additional actions
$4 \leq I_{VG} < 7$	Moderate	Periodic monitoring and preventive maintenance
$I_{VG} > 7$	Severe	Detailed analysis required to 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).

3.2 *Vulnerability curves*

Vulnerability curves constitute mathematical models that estimate the 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 (Abhas *et al*., 2013).

Accurate and detailed information regarding the materials, geometric configuration, structural system, number of storeys, and location is crucial. Regrettably, such information is often incomplete or unavailable. 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. The curves are prepared based on the identified aggravating factors, evaluating their influence on the frequency and behavior of events. The generation of these curves mainly requires to establish the input data: damage scale, building typology and intensity criteria.

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.

3.3 *Vulnerability to cracking*

Potential soil cracking zones within the city have been identified in a 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 adopted:

- 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.

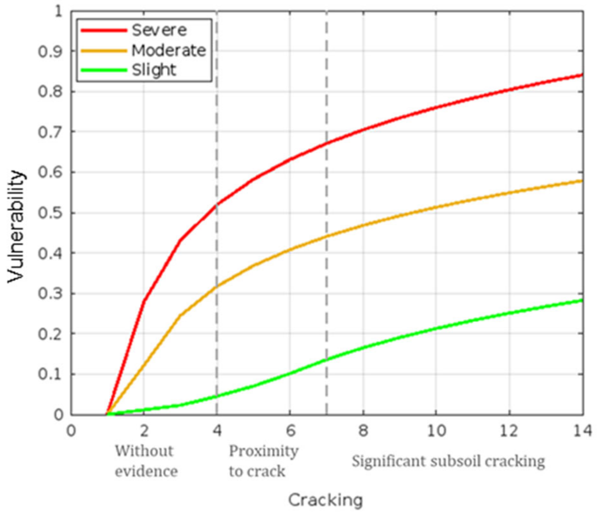

Figure 1. Vulnerability curves for shallow foundations on soft soils with high potential cracking.

The probability of damage varies depending on the vulnerability value obtained through the analysis. It was observed that when cracking is present in the subsoil, the probability of structural damage increases, particularly in buildings with unfavorable construction, geometric, or structural characteristics. It is important to highlight that this analysis is statistical and inherently dependent on the amount and quality of available data. Therefore, a complementary probabilistic analysis was carried out to enhance the reliability and align the results with current engineering standards

4 RELIABILITY OF SHALLOW FOUNDATIONS

In probabilistic terms, reliability is defined as the likelihood that a system will perform its intended functions correctly; it is mathematically expressed as the complement of the probability of failure.

There are three principal approaches to estimating probability. The first is empirical, in which probabilities are derived from the relative frequency of observed events. When sufficient data is available, a statistical model can be fitted to the dataset, allowing for the estimation of event probabilities. However, the accuracy of this method depends on the size and representativeness of the observed data. The second approach involves estimating joint probabilities or probability distributions of relevant variables, which is useful when direct observations are limited or unavailable. The third method is the Bayesian approach, which combines subjective judgment with available data to infer probabilistic outcomes.

In this study, it was not feasible to construct vulnerability curves for each foundation type due to the limited number of documented failure cases in the compiled database. To address this gap, a safety assessment using Monte Carlo simulation was implemented to evaluate the performance of a typical residential building—ranging from one to five-storey building—supported on a foundation slab over soft soils with cracking potential.

The conditions assumed in the simulation apply only to structures with characteristics similar to the modeled scenario. Load combinations were verified in accordance with the "Acciones" standard (2023), and both the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) were evaluated. The stratigraphic profile was idealized as follows:

- Dry crust – uncompacted sandy silt fill, with thicknesses ranging from 0 to 3 m.
- Upper clay formation – highly compressible lacustrine clay with low undrained shear strength, up to 20 m thick.
- Hard layer – competent bearing stratum beneath the clay.

It is assumed that all buildings are laterally confined (bounded by adjacent structures), and that total allowable settlement must comply with the code requirement of $\delta_t \leq 15$ cm. To incorporate the effect of subsoil cracking, the bearing capacity (r) was reduced by 10%, based on the geotechnical hazard conditions. This adjustment is supported by recent findings from Martínez-Galván (2024).

4.1 *Simulation by Monte Carlo technique*

A commonly used numerical method for estimating the probability of failure is the Monte Carlo method. In this study, the probability density parameters *N(μ, σ)* were derived from the database of real-world cases used to construct the cracking vulnerability curves shown in Figure 1. These statistical parameters served as the basis for generating random values for the input variables listed in Table 2.

For each simulation run, a random input vector was generated using the specified distributions, and the calculations defined in the design standard were performed to evaluate both the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS).

Table 2. Variables considered for simulation.

Variable	Interspace	Step	Variable type
Thickness Dry Crust	0 - 3 m	1m	Random
Upper Clay Formation	20 m	----	Depends on DC
Slab basement (B)	5 - 11 m	0.5m	Random
Slab length (L)	10 - 20 m	0.5m	Random
c_u (kPa)	15 - 50	0.1	Random
m_{vv} (cm²/kg)	0.1 - 0.45	---	Depends on UCF
Level load 13 kPa	1-5 storeys	---	Random
Eccentricity	0.1	Constant	Constant

A total of 11,000 iterations were performed, each representing a unique combination of input variables randomly sampled from the statistical distributions observed in the empirical database. For each case, the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS) were evaluated.

The simulation results, summarized in Figure 2 and Figure 3, indicate the following:

- Only 41 iterations exceeded the Ultimate Limit State, all of which corresponded to five-story buildings. These cases represent conditions of structural instability due to insufficient bearing capacity.
- A total of 1,090 iterations surpassed the allowable settlement threshold of 15 cm, indicating failure in terms of the Serviceability Limit State.

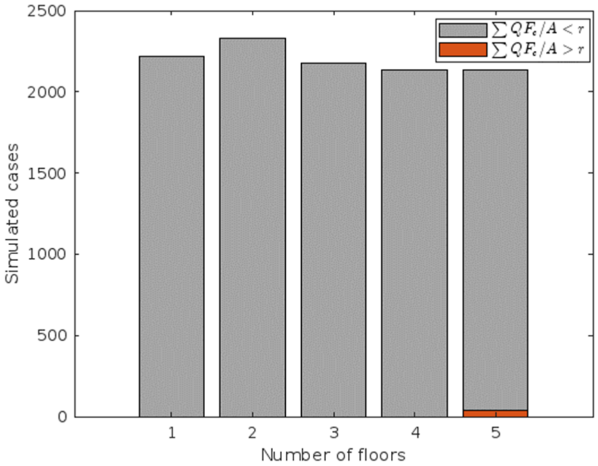

Figure 2. LFS statistics of the MC simulation according to the review by the standard for foundations.

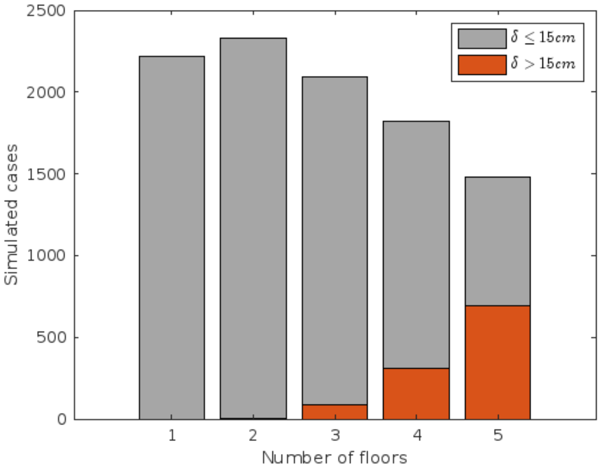

Figure 3. LSS statistics of the MC simulation according to the review by the standard for foundations

From the set of simulated buildings, the values of *Var(X)* and *E{X}* make it possible to have an approximation of the probability that the tolerable settlement is exceeded as:

$$P[|X-\mu| \leq k\sigma] \leq 1 - \frac{Var(X)}{k^2} \tag{1}$$

This type of inequality, characterized by the comparison of the probability of the distribution's tail and its expected value, is known as Chebyshev inequality. This inequality provides a conservative bound on the probability that a variable deviates significantly from its mean, making it suitable when the distribution is unknown or data is limited. The results obtained are presented in Table 3.

Table 3. Results of Chebyshev inequality for $P[\delta_T \geq 15]$.

N° Storeys	μ	σ	$P[\delta_T \geq 15]$
1	13.28	1.37	0.0000
2	10.09	1.15	0.0000
3	7.51	3.40	0.2065
4	2.52	4.56	0.2118
5	5.10	3.60	0.2868

4.2 *Development of fragility curve for LSS*

To estimate the probability of exceeding the allowable settlement defined by structural standards, the simulation results were analyzed by fitting a cumulative log-normal distribution function. This approach allowed the construction of fragility curves that effectively captured the statistical behavior of the simulated settlement data, Figure 4, providing a reliable approximation of exceedance probabilities across different building configurations.

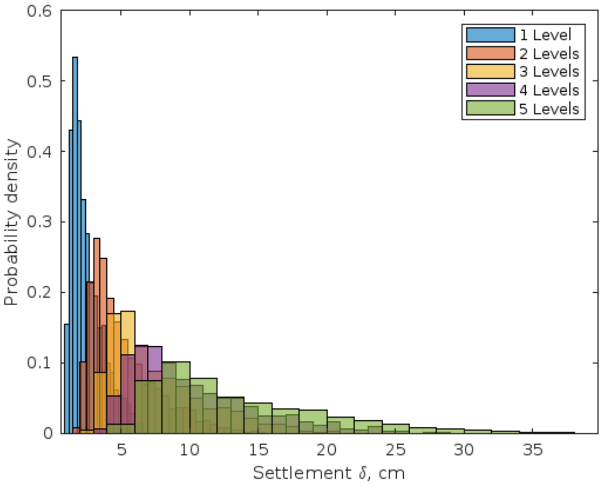

Figure 4. Probability density adjustment based on total settlement.

Although a log-normal distribution provided a good fit to the simulated settlement data, future research could examine the influence of non-lognormal tail behaviors, particularly in the case of taller buildings, where extreme settlements may not conform to the assumed distribution.

For this analysis, the dataset was filtered to classify buildings by the number of storeys, ranging from one to five. For each category, a probability density function was fitted to the simulated settlement values using a log-normal distribution. The distribution parameters μ and σ, corresponding to the mean and standard deviation of the logarithmic transformation were estimated through maximum likelihood methods and are summarized in Table 4.

Table 4. Parameters of the log-normal distribution of the dataset.

N° Storeys	σ	μ_1
1	0.43	0.83607
2	0.4314	1.5329
3	0.4235	1.9239
4	0.42365	2.2204
5	0.42351	2.4945

These parameters are then used to construct fragility curves, which represent the probability of exceeding the allowable settlement limit. The curves are fitted using a least-squares method to match the empirical failure data. Finally, the resulting fragility curves are plotted for each building height category.

The curves obtained are presented in Figure 5 and the associated probability distribution functions in Figure 6. It can be observed that, for a 1- to 2-story dwelling located in a potential cracking zone and with a foundation slab, the probability of developing a total settlement greater than that permitted by the standard is zero, $P(\delta_{T1-2} > 15) = 0$.

Overall, it can be observed that all cases, regardless of the number of storeys, will develop settlement. The probability changes as the applied load increases. Based on the simulation, a three-story building has a probability of exceeding the standard limit (15cm) of $P(\delta_{T3} > 15) = 0.228$, with four storeys the probability is $P(\delta_{T4} > 15) = 0.272$, and with five storeys the probability is $P(\delta_{T5} > 15) = 0.303$. Figure 6 shows the probability distribution function calculated for the case under analysis.

Therefore, the reliability of a slab foundation in soft soils with potential cracking is estimated to be 100% for buildings with one or two storeys.

In contrast, for buildings with three storeys, the reliability decreases to 77.2%; for four-story buildings, it drops to 72.8%; and for five-story buildings, it is approximately 69.7%.

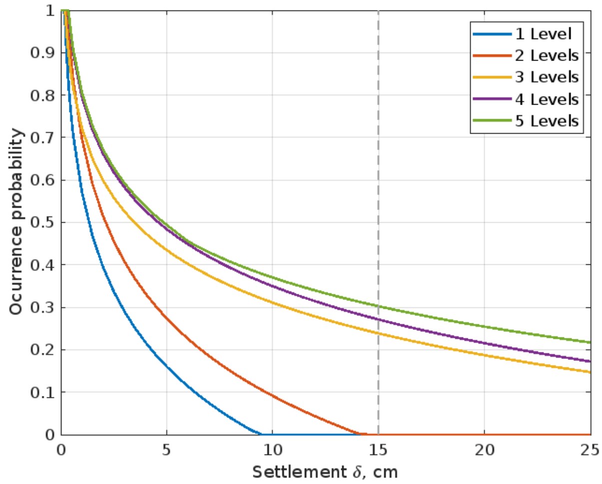

Figure 5. Fragility curve for the settlement analysis case.

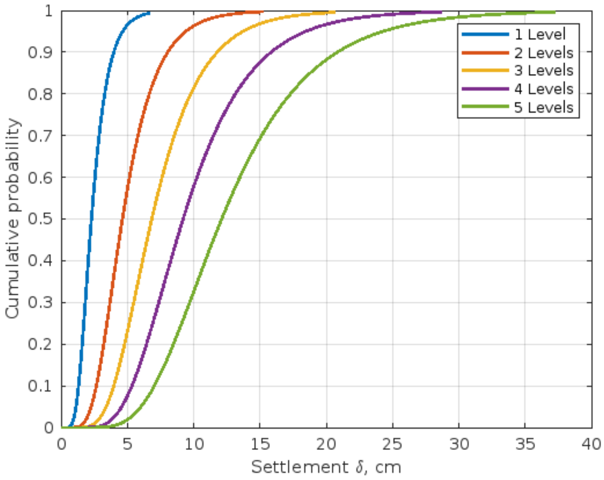

Figure 6. Probability distribution function of the analysis case.

The fragility curves derived from the simulation provide valuable insights for establishing risk thresholds and prioritizing interventions in areas with high potential to subsoil cracking. These curves can support the development of early warning systems, inform updates to building codes, and guide site-specific design decisions in urban planning. By quantifying the probability of exceeding tolerable settlement limits, engineers and decision-makers can better allocate resources and target mitigation efforts.

The failure probability of a system can be estimated by considering the individual probabilities of different events and their intersections, applying the Poincaré principle.

$$P[E] = P[E_1 \cup E_2 \cup, \dots, \cup E_k] = \\ = \sum_i P[E_i] - \sum_{i \neq j} P[E_i \cap E_j] + \sum_{i \neq j \neq l} P[E_i \cap E_j \cap E_l] - \dots \tag{2}$$

This approach is particularly useful when using the Monte Carlo technique. By solving the corresponding expression, it is possible to estimate the probability that a building does not meet the permissible settlement and ultimate resistance requirements established by current standards, Table 5.

The Poincaré principle allows for the approximation of system failure probability by accounting for the union and intersection of multiple failure events, useful in complex multi-variable systems.

Table 5. Probability of system failure by the Poincaré solution.

Building storey	P($E_r \cup E_\delta$)	Reliability
1 storey	0.000000	100.0%
2 storeys	0.000859	99.9%
3 storeys	0.077170	92.3%
4 storeys	0.125159	87.5%
5 storeys	0.305980	69.4%

The simulation conducted does not account for subsidence rates, differential settlements, or pre-existing or adjacent cracks. Furthermore, it is presumed that the structures examined are meticulously engineered and designed in accordance with the criteria stipulated in the Building Regulations. Consequently, the fragility curves presented are only valid for the specific case studied and are intended to serve as a reference for the expected behavior under similar conditions.

5 CONCLUSIONS

This study evaluated the reliability and vulnerability of shallow foundations on soft soils with high cracking potential in Mexico City. The main objective was to bridge the gap between observational assessments and probabilistic modeling to provide a more comprehensive framework for evaluating geotechnical risk in urban environments.

A significant discrepancy was identified between the damage probabilities derived from empirical vulnerability curves (Figure 1) and those obtained from fragility curves generated through Monte Carlo simulations (Figure 5). Field observations revealed that numerous low-rise buildings (fewer than three-storey building) located in high cracking potential zones experienced severe damage or even total collapse. Most of these structures were self-built and failed to meet the minimum design and construction standards established by local regulations.

This contrast underscores the importance of integrating empirical observations with probabilistic methods when evaluating geotechnical risk. The combined use of both approaches provides a more robust framework for assessing potential damage due to subsoil cracking, particularly in urban environments characterized by heterogeneous subsoil and widespread informal construction practices.

In Mexico City's soft soil zones, the primary design challenge lies in managing large ground deformations. Although newly constructed buildings increasingly incorporate improved safety considerations, a significant portion of the existing building stock remains vulnerable due to outdated design methodologies and lack of regulatory compliance.

The results of this study highlight the urgent need to implement preventive strategies such as geotechnical monitoring, probabilistic modeling, and site-specific vulnerability assessments to guide retrofitting efforts and risk management. Achieving resilient urban development will require not only the application of technical tools, but also policy interventions to enforce building codes, prioritize retrofitting, and integrate geotechnical risk assessments into urban planning and regulation.

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