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# Seismic vulnerability, municipality of Toluca: a holistic analysis of the structural, social and economic aspects

## Vulnerabilidad sísmica, municipio de Toluca: un análisis holístico de los aspectos estructurales, sociales y económicos

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## Abstract

This research integrates physical, social, and economic aspects to address seismic vulnerability in the municipality of Toluca, Mexico. The objective is to design and implement a procedure that estimates seismic vulnerability at the urban block scale. The developed method combines physical and socio-economic dimensions to assess seismic vulnerability. The physical dimension includes susceptibility to seismic resonance, as well as the age and type of constructions, while the socio-economic dimension is based on the marginalization index. Mapping covers 7,807 urban blocks where five levels of vulnerability are identified, with 46.6% exhibiting severe and very severe levels. The resulting zoning is a robust tool for risk reduction, particularly for justifying the implementation of actions aimed at reducing vulnerability.

**Keywords:** development management; seismic risk; hazard mapping; holistic approach; seismic resilience; seismic vulnerability.

## Resumen

La investigación transita hacia la integración de aspectos físicos, sociales y económicos, que convergen en una aproximación a la vulnerabilidad sísmica para el municipio de Toluca, México. El objetivo se orienta a diseñar y aplicar un procedimiento que estime la vulnerabilidad sísmica a escala de manzana urbana. El método desarrollado fusiona las dimensiones físicas y socioeconómica para evaluar la vulnerabilidad sísmica. La dimensión física incluye la susceptibilidad a resonancias sísmicas, la antigüedad y tipo de construcciones; mientras que la socioeconómica se basa en el índice de marginación. La cartografía cubre 7.807 manzanas urbanas donde convergen cinco niveles de vulnerabilidad, destacando que, el 46,6% muestra niveles altos y muy altos. La zonificación resultante es una herramienta robusta para la reducción del riesgo, especialmente para justificar la implementación de acciones dirigidas a reducir la vulnerabilidad.

**Palabras clave:** gestión del desarrollo; riesgo sísmico; cartografía de peligros; enfoque holístico; resiliencia sísmica; vulnerabilidad sísmica.

# 1. Introduction

Socio-natural disasters, especially earthquakes, pose significant hazard to the safety and well-being of communities worldwide. Faced with the hazard of a seismic event, the analysis and understanding of vulnerability become crucial tasks. Vulnerability to seismic risk is a concept that encompasses different dimensions, including structural, social, and economic aspects (Olcina, 2022). Therefore, adopting a holistic approach that considers these dimensions is essential to comprehend the true extent of seismic vulnerability and to develop effective mitigation and response strategies (Lee & Oh, 2022).

In this context, Disaster Risk Reduction (RRD) emerges as a pivotal field in emergency management and urban planning. Essentially, DRR refers to a series of actions and strategies aimed at minimizing the adverse effects of natural or human-induced events (Parajuli, 2020). However, its effectiveness largely depends on the understanding and addressing overall vulnerability.

Vulnerability, according to the Dictionary of the Royal Spanish Academy (DRAE, 2014, for its acronym in Spanish), is the quality of being susceptible to harm or damage, whether physical or moral. This multidimensional concept involves evaluating the structural conditions of a society or region in terms of its capacity to resist. Essentially, vulnerability represents the latent possibility of experiencing harm before an adverse event occurs, emphasizing the importance of strengthening conditions that enable a community to face and overcome challenges.

This concept explains why territories exposed to the same hazard may experience different impacts, unevenly distributing the effects of natural hazards. Vulnerability is understood as a component of risk, alongside the hazard and exposure (Tatano et al., 2023).

The hazard is a physical characteristic; however, exposure and vulnerability are influenced by social and economic factors, delineating socio-economic inequalities (Iglesias-Lesaga & Carmona-Motolinia, 2016; Pérez-Morente et al., 2017; Baró & Monroy, 2018; Ramos, 2019).

Vulnerability is a concept that encompasses various dimensions, enabling the development of effective DRR strategies that strengthen community resilience to disasters (Conlon et al., 2020). In this sense, the assessment presented here considers structural, social, and economic dimensions.

The studies by Acevedo et al. (2017 & 2020), along with the work of Hoyos & Hernández (2021), focus on assessing the structural vulnerability of buildings, considering physical aspects such as construction type, age, conservation status, material resistance, and foundation. Research conducted by Armaş (2012); Huang et al. (2015); Burton et al. (2022) focuses on analyzing the social and economic conditions that expose communities to higher risks during seismic events. Factors that can be evaluated to estimate social and economic vulnerability include the population's income level, availability of health and emergency services, population density in risk-prone areas, education, and public awareness of earthquake preparedness, as well as the responsiveness and recovery capacity of local institutions.

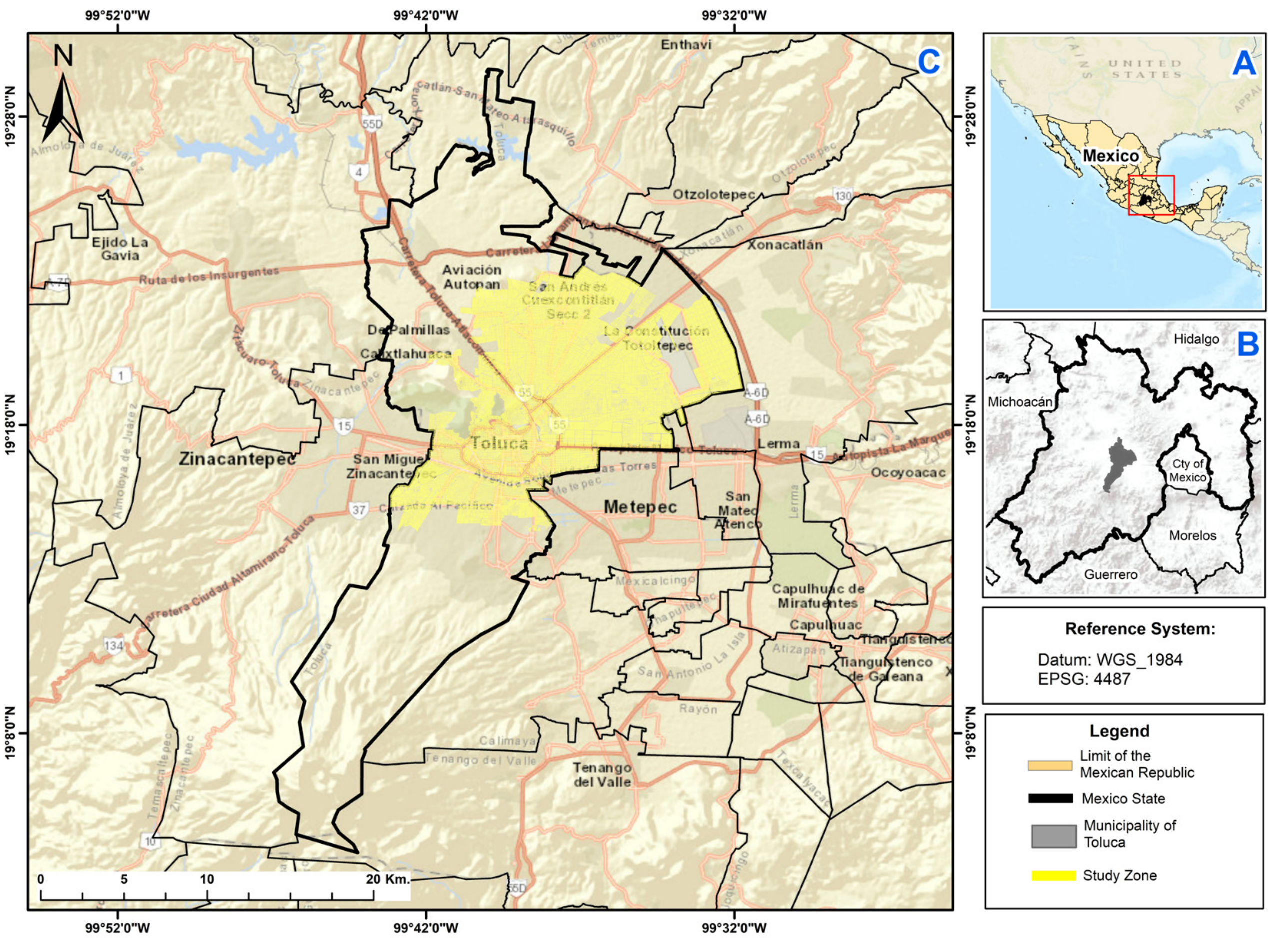
The main objective of this research is to integrate existing methods that rarely converge in a single study, especially when analyzing seismic vulnerability at the municipal level. The innovative aspect of this work does not lie in generating a new method; rather, its strength lies in combining approaches from both applied and social sciences. Cardona (2001) and Barrantes & Márquez (2011) engage in deep academic discussions on interdisciplinary integration to achieve robust studies. Particularly, for the case study conducted in this article (municipality of Toluca), factors of structural and socioeconomic vulnerability are considered. The procedure systematically combines technical resources and information available for the Mexican context, opening up the possibility of replication in other municipalities of the country. Lastly, the goal is to enhance the quality of information for the case study. Until now, the only previous work corresponds to Ordaz Hernández et al. (2020), which focused on analyzing structural vulnerability and only considered building typology and ages.

# 2. Methodology

## 2.1. Study area

The study was conducted in the city of Toluca, the capital of the State of Mexico, which is home to a population of 910,608 inhabitants (National Institute of Statistics and Geography [INEGI], 2020a) (Figure 1). The urban infrastructure is organized into 7,807 blocks, with a prevalence of buildings between two and five floors, distributed over an area 131.08 km$^2$ at an average altitude of 2,640 meters above sea level (Ministry of Agrarian, Territorial, and Urban Development [SEDATU], 2020).

Figure 1. Geographic location of the city of Toluca




Where: Box A represents the context in Central and North America, Box B indicates the location within the state, and Box C denotes the city's position within the municipality

Source: INEGI (2020b). Own elaboration

Due to urban expansion and population growth in Toluca, there is a growing concern about the structural vulnerability of buildings. The rapid construction of housing and the lack of adequate regulation in some areas have resulted in building practices that may be susceptible to damage in the event of seismic events or other natural hazards. For instance, between 2000 and 2020, the city's population increased from 666,596 to 910,608 inhabitants (INEGI, 2010 & 2020b). In a qualitative study on the structural vulnerability to seismic hazard in the city's housing stock, Ordaz Hernández et al. (2020) warned about a significant number of blocks susceptible to damage. In the cited study, 5,121 blocks were analyzed, of which 866 were predicted to have very severe vulnerability and 1,430 with severe vulnerability.

In the context of the described exposed elements, stratigraphic characteristics that contribute to local seismic amplification are added. For the city of Toluca, impedance contrast values above 3.0 and dominant ground periods exceeding 1.0 s have been estimated, spatially linked to sites with powerful layers of loosely consolidated (low density) soils up to 100 meters thick (Sánchez et al., 2022; Ordaz Hernández, 2022). The significance of this is heightened considering the location of the city of Toluca within the MVB seismotectonic zone (Zúñiga et al., 2017), the same structure that generated the magnitude 7.2 Mw, earthquake on September 19th, 2017, causing the death of at least 369 people (Buendía & Reinoso, 2019).

## 2.2. Materials and methods

Within a city, two approaches can be followed depending on the research object. The first is related to studies of a particular building or construction, which, due to their relevance, justify detailed analysis, as is the case with structural modeling. Examples of these applications have been developed in heritage buildings in the cities of Malaga and Cairo (Goded, 2010; Sallam et al., 2023), or for the analysis of the vulnerability of lifeline buildings in Uttarakhand, northern India (Girish et al., 2019).

However, the work presented here aims to approach seismic vulnerability conditions in a city (second approach), using the block as the basic unit of information. Studies on seismic vulnerability at the city level face the challenge of handling a significant volume of alphanumeric data and grouping buildings with similar structural behaviors (Armaş, 2012; Hassan et al., 2022; Li & Formisano, 2023). In cases where information is incomplete or it is unfeasible to obtain it directly in the field, some studies apply convolutional neural networks to automatically detect building typologies (Cui et al., 2023; Hafidz et al., 2024).

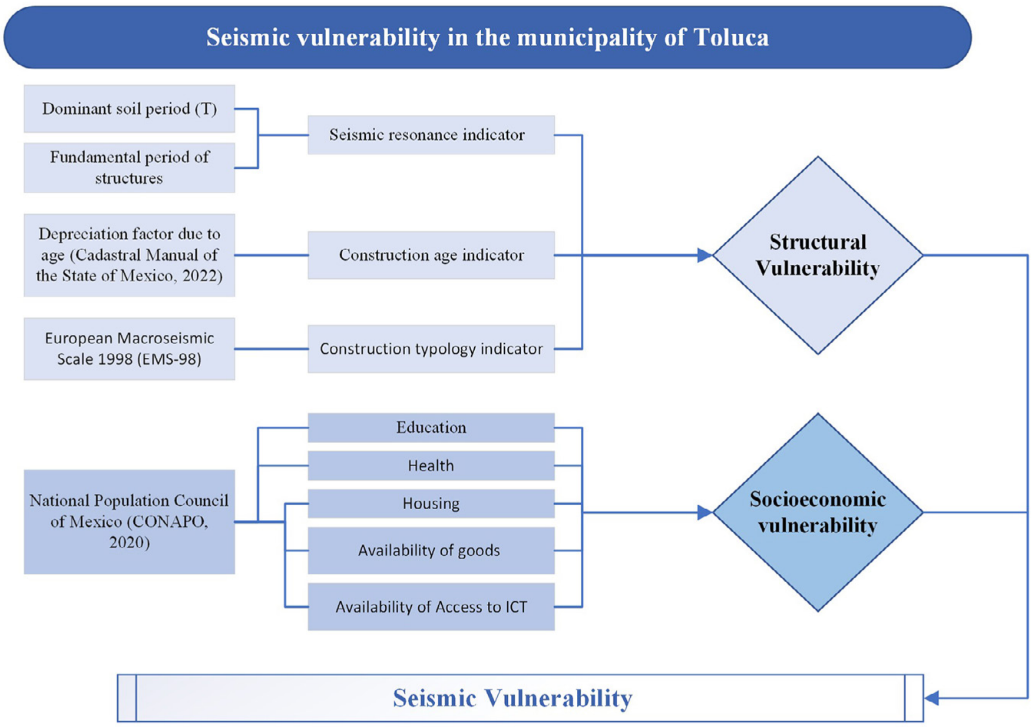
In coherence with the objective of this study, a procedure was designed that led to obtaining seismic vulnerability ($V_S$) (Figure 2). The methodological proposal is based on the analysis of two vulnerabilities: Structural vulnerability ($V_e$) and socioeconomic vulnerability ($V_{se}$) (Equation 1). Its purpose is to generate a cartographic product that approximates the physical and socioeconomic reality of the municipality of Toluca and that, moreover, can be replicated in other municipalities of Mexico.

Seismic vulnerability requires a holistic analysis, in this case, supported by the spatial relationships between structural and socioeconomic vulnerability. These vulnerabilities and the indicators that compose them are extensively used for different case studies (Baquedano et al., 2023; Jaimes et al., 2023; Meyers-Angulo et al., 2023; Novelo-Casanova & Suárez, 2024). However, the procedure explained below can be strengthened in subsequent studies, for example, by analyzing the preparedness and response capacity of government structures, defined in the literature as institutional vulnerability (Acuña, 2016; Alcántara et al., 2019; Muñoz-Sánchez, 2019).

$$V_S = V_e + V_{se} \quad \text{Equation 1}$$

For the formulation, the same weights were assigned to the variables $V_e$ and $V_{se}$. This selection, made through expert criteria, aims to achieve a balance in the contribution of both variables, ensuring that the equation fairly reflects their impact on total vulnerability.

Figure 2. Flow chart for determining seismic vulnerability




Own elaboration

### 2.2.1. Structural vulnerability

The assessment of structural vulnerability involves analyzing and evaluating the level of fragility of structural elements of a building against seismic events (Martins & Silva, 2021) and is considered one of the most complex variables to estimate. Generally, there are two types of studies: (1) those aimed at defining the vulnerability of a particular structure (building, bridge, dam, among others) (Vargas et al., 2013; Alas & Grijalva, 2018; Cárdenas, 2021) and (2) those aimed at estimating the vulnerability of a set of structures that are part of a neighborhood, city, or municipality, where constructions with probably similar behaviors are grouped (Armaş, 2012; Ruiz et al., 2016; Ordaz-Hernández et al., 2020; Colajanni & D'Anna, 2024). For the present study, the second approach is applied (vulnerability index method), using the block as the basic unit of information (Equation 2).

Ve= Irs + Iec + Itc Equation 2

Where Irs, Iec and Itc correspond to the seismic resonance, age of constructions, and construction typology indicators, respectively. This choice implies that each of these indicators is considered to contribute equivalently to the overall assessment.

#### *2.2.1.1. Seismic resonance indicator*

In the case of Mexico City, located approximately 70 km from Toluca, the effect of seismic resonance on infrastructure has been demonstrated (Orozco & Reinoso, 2007; Razo & Domínguez, 2020). These studies have shown the relationship between seismic resonance and the damages caused to structures by the earthquakes in July 1957, September 1985, and September 2017. For this work, the definition proposed by Orozco and Reynoso (2007) is considered: "The resonance effect is considered to occur when, during seismic excitation, the natural period of a structure is very similar to the dominant period of the soil on which it is founded." (p. 83).

Based on this theoretical foundation, the present study addresses the dominant soil period, obtained through the application of the empirical equation T=(4H/Vs), proposed by Bard (1997) and applied in more recent studies (Rocabado et al., 2011; Diaz-Segura, 2017). In Bard's proposal, sediments thickness (H), and the shear wave velocity (Vs) are involved. It's important to highlight that the use of this method constitutes a simplification; however, it can be an alternative for urban areas similar to Toluca that lack seismic microzonation. The sediment thickness (H) was acquired through information from 20 boreholes located in the area for hydrological purposes (Expósito, 2012) and 66 boreholes from geotechnical studies conducted from 1992 to 2021 by the Materials Laboratory of the Autonomous University of the State of Mexico. The thickness of unconsolidated materials (H), ranges widely, from 0 to 140.0 m. In the work carried out by Sánchez et al. (2022), modeling of the different lithologies of the metropolitan area of the Toluca Valley was performed. Geotechnical boreholes (of shallow depth) allowed certainty of thicknesses up to the first approximately 25 meters, while boreholes with hydrogeological purposes (average depth of 150 m) clarified the depth of the rock stratum roof.

The most commonly used drilling method in geotechnical investigations in the municipality was the Standard Penetration Test (SPT). This allowed characterizing each soil layer based on the recorded number of blows (N). In this way, it was possible to apply the empirical correlations proposed by Dikmen (2009), which are based on the number of blows (N), to obtain the shear wave velocities (Vs) of the soils in the area (Table 1). Considering the vertical heterogeneity of the cross-section (intercalation of different layers), the equivalent Vs was determined using the equation (Federal Electricity Commission [CFE], 2015):

$$V_S = \frac{\sum_{i=1}^{N} V_i h_i}{H_S}$$

Where $V_i$ corresponds to the shear wave velocity of each layer, $h_i$ represents the thickness of each layer, and $H_s$ represents the total of all thickness. Subsequently, the dominant period of the soil was calculated for the 86 points (boreholes), and the obtained value was interpolated using the geostatistical Kriging method.

Once the approximate values of the dominant period of the soil, on which the urban infrastructure rests, have been clarified, the next step is to estimate the oscillation period of the structures (Te). For this purpose, various numerical simulations are available, which can be consulted in Oliveira & Navarro (2010). Considering the height of the constructions in the municipality, it was decided to use the National Earthquake Hazards Reduction Program (NEHRP,1994), indicating that Te=0.1 N, where N represents the number of levels with a minimum height of 2.7 meters per floor. The values of Te were associated with the blocks according to the number of levels (height) most generalized around their perimeter. Then, an overlay was performed between the blocks and the map of the dominant period of the soil. This allowed calculating the T/Te ratio for each block. Buildings would experience resonance when the results of the ratio fall within the range of 0.7 to 1.2, (Federal District Building Regulations [RCDF], 2004), and polygons in this situation are assigned a weighting value of 1.0, while the rest are assigned 0 (Figure 3A).

Table 1. Lithological types forming the subsurface of the municipality of Toluca and their shear wave velocities

| Lithological type | Shear wave velocity ($Vs_{30}$ in m/s) |
|---|---|
| Inorganic clays with low to medium plasticity | 161.42 m/s* |
| Inorganic silts and very fine sands | 166.51 m/s* |
| Well-graded sands | 216.61 m/s* |
| Clayey sands | 202.45 m/s* |
| Inorganic silts | 176.19 m/s* |
| Silty sands | 205.44 m/s* |
| Poorly-graded sands | 235.97 m/s* |
| Poorly-graded gravels | 229.09 m/s* |
| Pyroclastic material | 760-1,500 m/s** |
| Volcanic rock (Andesite) | >1,500 m/s** |
| Volcanic rock (Basalt) | >1,500 m/s** |

Source: *Values obtained applying empirical correlations proposed by Dikmen (2009). **Shear wave velocities proposed by Federal Emergency Management Agency (FEMA, 2003) for lithological types like those studied in this case study; Own elaboration

#### *2.2.1.2. Construction age indicator*

For the analysis of the influence of age (Figure 3B), the suggestions contained in Serrano & Temes (2015) and Tinoco et al. (2019) were considered. Additionally, the Cadastral Manual of the State of Mexico (Institute of Geographic, Statistical and Cadastral Information and Research of the State of Mexico [IGECEM], 2022b) was consulted, which proposes the period of useful life for constructive typologies (Example: H1, precarious housing typology with 15 years of useful life). The analysis of the cited works refers to (1) the incidence of aging of structures on their resistance capacity against seismic events and (2) the construction period, which likely suggests improvements in safety protocols in design. The two mentioned approaches were attempted to be summarized in Table 2, and with the support of SQL queries in GIS platform, possible options were identified. The age of different constructive developments for Toluca is extracted from IGECEM, (2022a). The second element to consider refers to the enforcement of the General Regulation of Constructions of the Municipality of Toluca (Municipal Government of Toluca, 1993), where explicitly in the Tenth Title "Structural Safety", in chapters I to VI stipulate actions aimed at improving construction protocols (Ramírez et al., 2002).

Table 2. Integration of factors associated with the age of constructions

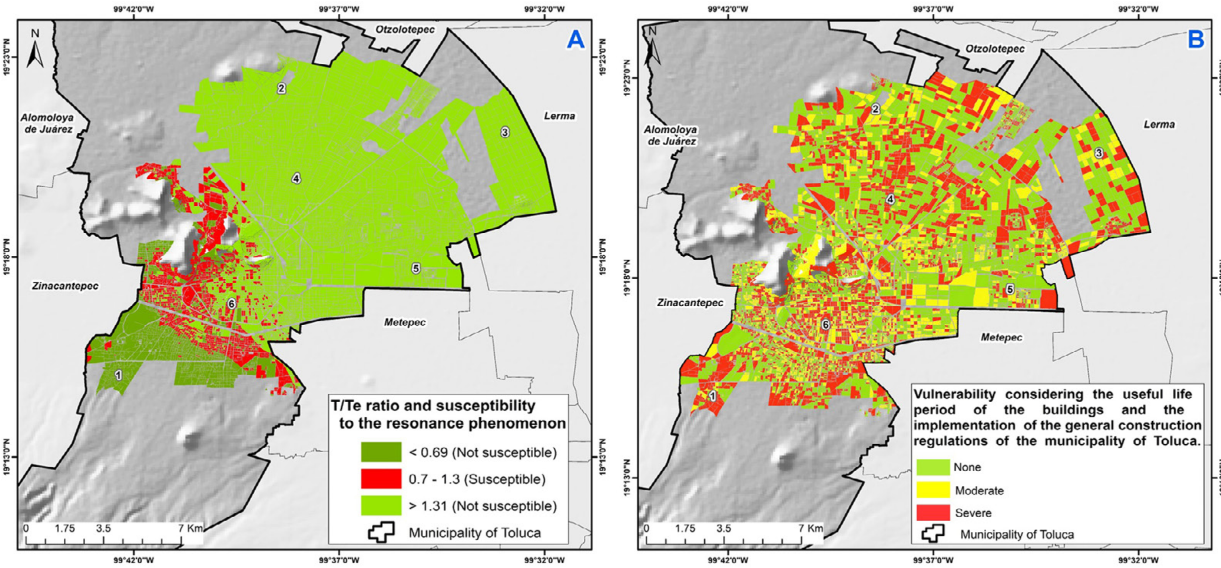
| Null vulnerability Weight value 0 | Moderate vulnerability Weight value 0.5 | Moderate vulnerability Weight value 0.5 | Severe vulnerability Weight value 1 |
|---|---|---|---|
| Construction exceeding the useful life period | Construction exceeding the useful life period | Construction not exceeding the useful life period | Construction exceeding the useful life period |
| Construction post-enforcement of the General Regulation of Constructions of the Municipality of Toluca | Construction post-enforcement of the General Regulation of Constructions of the Municipality of Toluca | Construction pre-enforcement of the General Regulation of Constructions of the Municipality of Toluca | Construction pre-enforcement of the General Regulation of Constructions of the Municipality of Toluca |

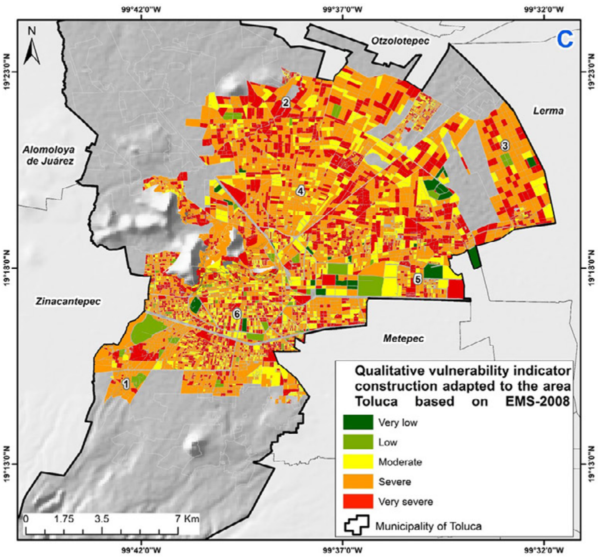
Own elaboration

#### *2.2.1.3. Construction typology indicator*

Up to this point, seismic resonance and building age indicators have been described. Now, building typology is addressed. In this case study, a large volume of data is employed, analyzing approximately 157,365 dwellings distributed across 7,807 blocks. The building typology indicator (Figure 3C) is introduced as a third criterion to define the predisposition of structures to suffer damage during seismic events. Martins & Silva (2021) indicate that seismic performance assessments of buildings can follow two routes: (1) through empirical methods (Iglesias Asenjo et al., 2006; European Seismological Commission, 2008; Novelo-Casanova & Suárez, 2024, among others) or (2) employing analytical methods (Federal Emergency Management Agency and National Institute of Building Sciences [FEMA/NIBS], 1999; NIBS, 2000; Milutinovic & Trendafiloski, 2003; Molina et al., 2010).

Figure 3. Spatial behavior of the indicators used for the analysis of structural vulnerability in the municipality of Toluca




| Indicator | | Number of Blocks |
|---|---|---|
| Susceptibility of Structures to Resonance | | 1,430 |
| Exceeding the Useful Life Period of the Structures | | 3,220 |
| Buildings constructed before the enforcement of the Regulation | | 3,711 |
| Vulnerability Measurement in Construction Typologies | Very Severe | 1,304 |
| | Severe | 2,793 |
| | Moderate | 256 |
| | Low | 2,726 |
| | Very Low | 728 |
| **Total blocks** | | **7,807** |

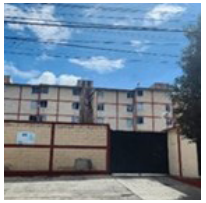
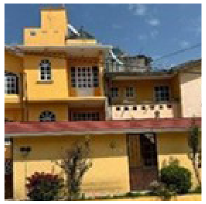
| Identifier | Colony name |
|---|---|
| 1 | Cacalomacán |
| 2 | Jicaltepec Autopan |
| 3 | La Constitución Toltepec |
| 4 | San Cristóbal Huichochitlán |
| 5 | Santa María Totoltepec |
| 6 | Toluca de Lerdo |

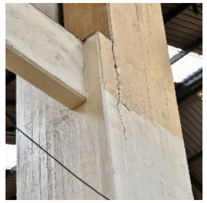
Where Box A represents the seismic resonance indicator, Box B represents the age of constructions indicator, and Box C corresponds to the constructive typology indicator

Own elaboration

Considering the current level of information available for the municipality of Toluca, the empirical methods approach will be pursued, where two criteria will be evaluated: (1) materials and construction design employed, and (2) experiences of damage to similar structures during historical earthquakes in Mexico. For a detailed analysis of the two aforementioned criteria, the cartography provided by IGECEM (2022a), is used as a starting point, which includes the blocks of the municipality and is associated with the attribute “Typology”. The typologies identified in the municipality of Toluca are exhaustively described in the Cadastre Manual of the State of Mexico IGECEM (2022b). This allowed correlating the structures of the municipality with similar ones that suffered different degrees of damage in past earthquakes (Ramírez & Lugo, 2000; González et al., 2010; Buendía & Reinoso, 2019; González et al., 2020; Tena-Colunga et al., 2021). Additionally, the vulnerability classes contained in the European Macroseismic Scale EMS-98 were observed, the latter serving as a validation reference for the decisions made. Thus, Table 3 tabulates (a) the eleven construction typologies present in Toluca, (b) the most common materials and design styles, (c) a representative image, (d) a qualitative assessment of their predisposition to suffer damage with an assigned weighting value, and (e) equivalent (similar) structures that suffered damage in past earthquakes. It is important to note that the procedure results in an approximation or preliminary evaluation of the “building typology” indicator, consistent with the level of information currently available to municipalities in Mexico; and the authors consider it important for future work to transition to the estimation of a Seismic Structural Vulnerability Index, similar to the proposal by Novelo & Suárez (2024).

Table 3. Predisposition of building typologies to suffer damage during seismic events. Qualitative approach for the municipality of Toluca

| Typology / Materials and Design Styles | Representative Image for Toluca / Qualitative Assessment of Susceptibility to Damage | Damage to Similar Structures in Past Earthquakes in Mexico |
|---|---|---|
| Informal housing (H1) / Precarious dwellings, without formal design. Poor-quality and/or recycled materials, unfinished. Room heights less than 3.0 m, self-construction. Construction surfaces are minimal, generally 40 $m^2$ or smaller. Roofing materials include cardboard sheets, tiles, asbestos, galvanized sheets. Wood, adobe, and recycled material are used in walls. |  Adobe construction in Toluca municipality / Very severe susceptibility to damage, **weighting value 1.0**. |  Collapse of walls and roofs in adobe constructions in the northern region of Guerrero State, during the earthquake on 19/09/2017 (8.1 Mw). |
| Popular housing (H2) / Economical housing without a defined or partially defined project. Economical materials, with rudimentary finishes, executed with poor quality. Room heights less than 3.5 meters, self-construction. Materials used include concrete, unfinished slabs, brick walls, or similar in walls. |  Economical housing without a defined project / Severe susceptibility to damage, **weighting value 0.8.** |  Cracks in columns and walls in economical housing without defined projects in the State of Chiapas, during the earthquake on 07/09/2017 (8.2 Mw). |
| Social Interest Housing (H3) / With a defined typical project. Economical materials with medium-quality execution. Room heights less than 3.5 m. Mass production by private or official companies. Located in urban areas, subdivisions, or isolated lots. Roofing may be concrete, pre-mixed concrete, glass block walls, brick, or similar. |  Social interest housing with a defined typical project / Moderate susceptibility to damage, **weighting value 0.6.** |  Partial deterioration of surface finishes in social interest housing with a defined project in Mexico City, during the earthquake on 19/09/2017 (8.1 Mw). |
| Medium Housing (H4) / Housing with regular, well-defined projects. Materials of medium and good quality with well-executed finishes. Room heights averaging 4.0 m, constructed under professional supervision. Materials used include concrete and vaults. Roofing typically employs waterproofing and tile and/or brick coverings. Walls are made of brick, concrete block, adobe, or stone. |  Medium housing with a well-defined regular project / Moderate susceptibility to damage, **weighting value 0.6.** |  Cracks in columns and beams, and in structural walls with defined projects in the State of Chiapas, during the earthquake on 07/09/2017 (8.2 Mw). |

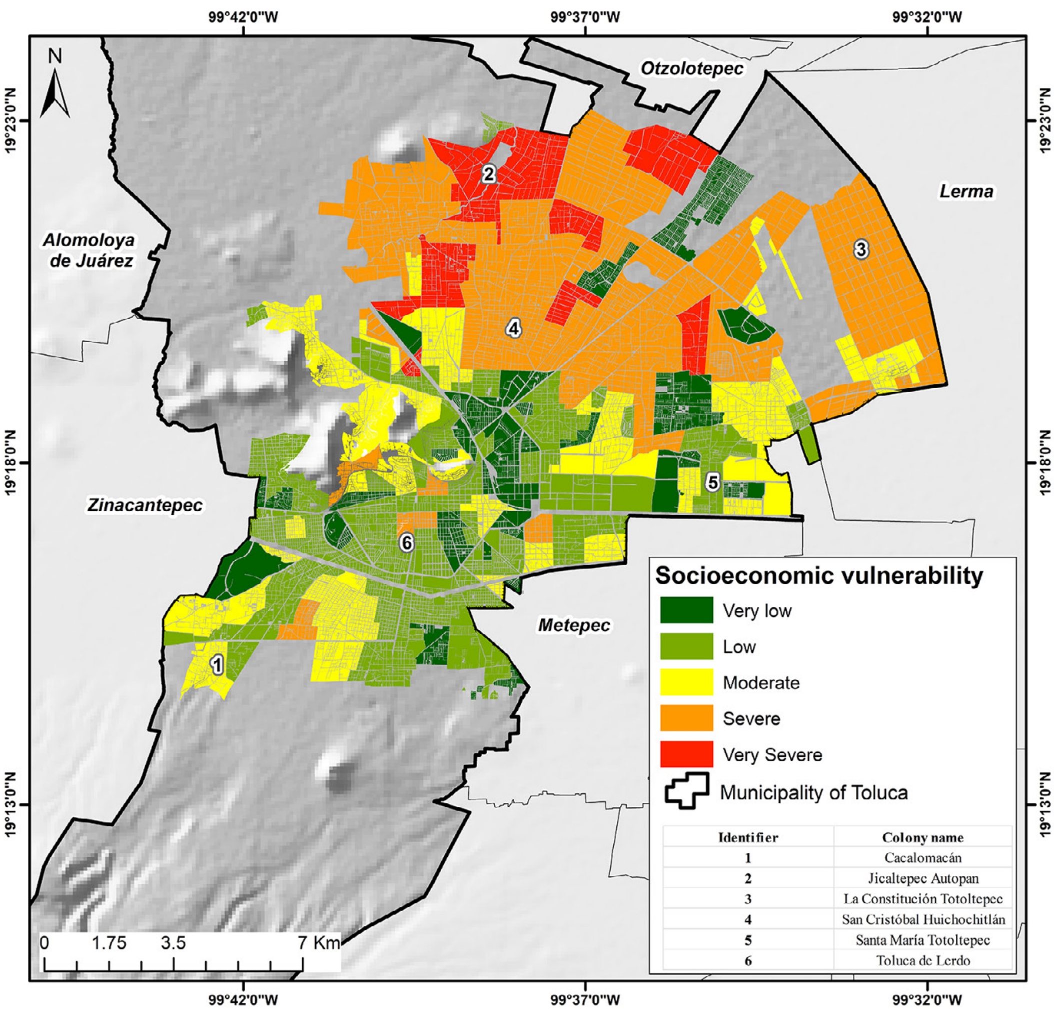
| | | | | |
|---|---|---|---|---|
| Good Residential Housing (H5) / Houses with good architectural design, functional and quality. Good-quality materials, well-executed finishes with special details. Room heights averaging 6.0 meters, constructed by construction companies. Located in exclusive areas and/or residential subdivisions. |  | Good residential housing with functional architectural design / Low susceptibility to damage, **weighting value 0.4.** |  | Partial deterioration of surface finishes without structural damage, residential area of Toluca City, during the earthquake on 19/09/2017 (8.1 Mw). |
| Medium Commercial (C2) / Commercial use constructions. Regular, defined, and functional project. Medium-quality materials with well-executed finishes. Room heights averaging less than 4.0 meters, constructed under supervision or by construction companies. Located in commercial zones, planned commercial corridors, or outside urban areas. |  | Medium commercial with a defined and functional regular project / Low susceptibility to damage, **weighting value 0.4.** |  | Cracks in columns without damage to structural walls with a defined project in Toluca, Mexico, during the earthquake on 19/09/2017 (8.1 Mw). |
| High Commercial (C3) / Defined, quality functional project, controlled high-quality materials, well-executed finishes with special details, average room heights of 6.0 meters, constructed by construction companies, high-quality and meticulously executed materials. |  | High commercial with a defined and high-quality functional project / Very low susceptibility to damage, **weighting value 0.2.** | | No evidence of structural damage, except for the fall of products and shelves during the earthquake on 19/09/2017 (8.1 Mw). |
| Light Industrial (I2) / Defined project, materials ranging from good to medium quality, room heights of over 10 meters, with structural horizontal elements over 1.10 meters, construction by construction companies, typically in industrial parks. |  | Light industrial with a defined project and high-quality materials / Very low susceptibility to damage, **weighting value 0.2.** |  | Falling domes, without structural damage with a defined project in the State of Chiapas, during the earthquake on 07/09/2017 (8.2 Mw). |
| Equipment (E1) / Buildings with architectural design. Masonry of hollow pieces with interior reinforcements and foundation chains. Walls with extruded blocks, with castles and closure chains. Metal beams and columns, zinc and painted zinc sheets, reinforcement with metal crossbars and stiffening diagonals. This category includes markets, schools, clinics, administrative hospitals, among others. |  | Special buildings with a defined architectural design / Very low susceptibility to damage, **weighting value 0.2.** |  | Cracks in walls and facades, without structural damage in special buildings in the State of Chiapas, during the earthquake on 07/09/2017 (8.2 Mw). |

Source: Data and photographs from various publications (Sol de Toluca, 2022; González et al., 2020; Buendía & Reinoso, 2019); Own elaboration

### 2.2.2. Socioeconomic vulnerability

To analyze socioeconomic vulnerability conditions in the municipality of Toluca, data published by the National Population Council of Mexico (CONAPO, for its acronym in Spanish) regarding the 2020 marginalization index were utilized (CONAPO, 2020a). The marginalization index estimated by CONAPO provides insights into economic, educational, and access-to-basic-services deficiencies, among others, experienced by communities. Currently, for the case of Mexico, it is considered the most robust index for designing programs aimed at connecting the population to economic and social development (Cortés & Vargas, 2011; Bernal & Mungaray, 2017; Peláez, 2023). The cartography reflecting the spatial behavior of the marginalization index was obtained from CONAPO (2020a) (Figure 4), and the indicators comprising the index are thoroughly explained in CONAPO (2020b).

Figure 4. Socioeconomic vulnerability, based on the marginalization index proposed by CONAPO (2020a)




Source: CONAPO (2020a)

The cartography representing socioeconomic vulnerability, according to the CONAPO's methodology (2020b), considers, among its indicators: (a) total population, (b) percentage of the population aged 6 to 14 not attending school, (c) percentage of the population aged 15 and over without basic education, (d) percentage of the population without access to health services, (e) percentage of occupants in inhabited private housing without drainage, (f) percentage of the population without access to piped water, (g) percentage of the population without access to electricity, (h) percentage of occupants in inhabited private housing with earthen floors, (i) percentage of occupants in inhabited private housing with overcrowding, (j) percentage of occupants in inhabited private housing without access to the internet and without access to cell phones. Each indicator is measured through variables, for example: education is estimated using the percentage of the population aged 6 to 14 not attending school and the percentage of the population aged 15 and over without basic education (CONAPO, 2020b). The marginalization index is used to understand social vulnerability to hazards of natural origin, especially seismic hazards. Communities with a severe marginalization index are likely to have a lower risk perception, less access to technologies for early warning systems, among other deficiencies. This approach provides a solid and objective foundation for understanding socio-economic disparities in the area, which is essential for formulating strategies and policies aimed at addressing the needs of vulnerable populations.

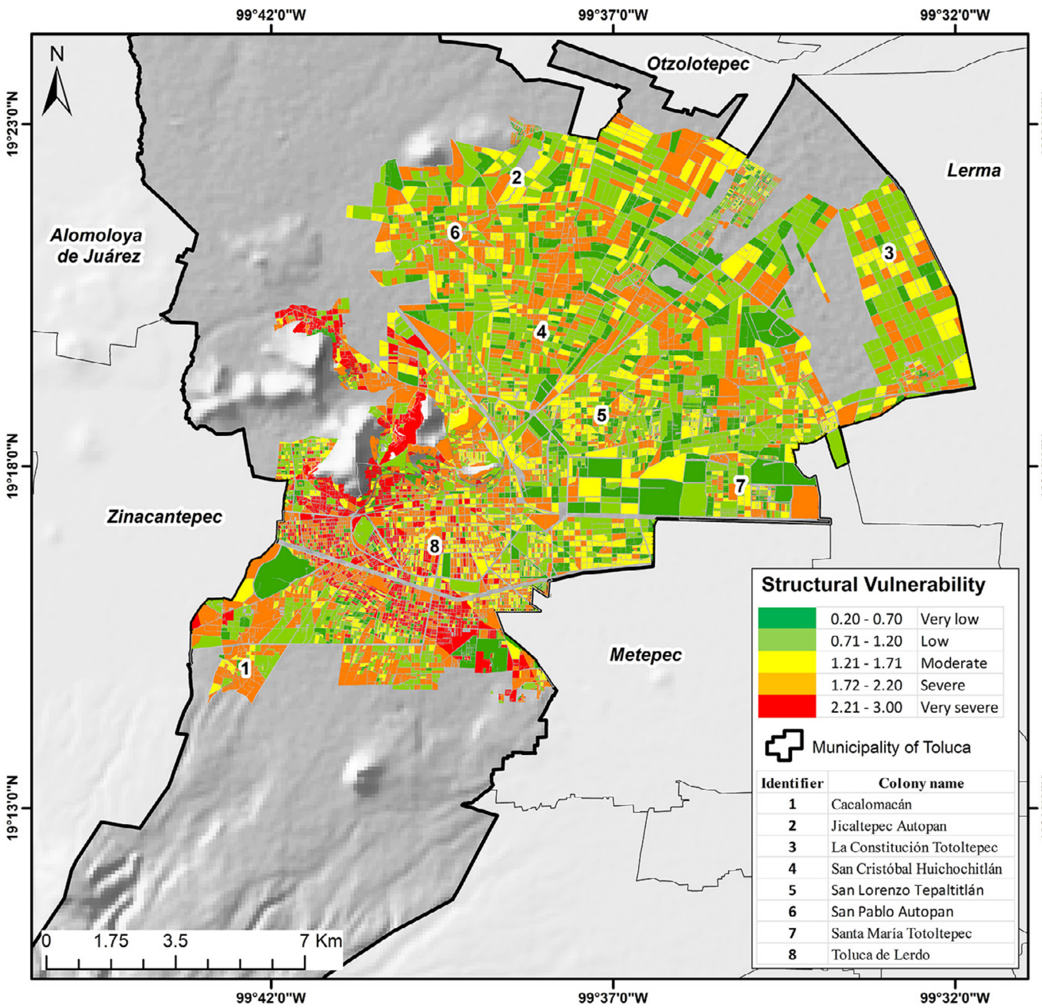
The cartography proposed by CONAPO (2020a) and considered in this study as socioeconomic vulnerability, establishes its stratification into five levels: Very severe, Severe, Medium, Low and Very Low. These levels are assigned weights of 1.0; 0.8; 0.6; 0.4 and 0.2, respectively, to subsequently integrate this result into the estimation of seismic vulnerability of the municipality.

# 3. Results

## 3.1. Structural vulnerability

The resulting cartography of structural vulnerability is achieved by summing the “weight value” attribute contained in the layers of the three involved indicators (seismic resonance, age of constructions, and construction typology) explained in the previous section (Figure 5). The three indicators are scaled from 0 to 1, with the sum of the indicators yielding a minimum of 0.2 and maximum of 3.0; while the intervals were established with the support of the Principal Components and Dalenius and Hodges methods explained in Lee & Oh (2022) and commonly applied in risk studies (Díaz et al., 2020; Eboh et al., 2021; Saha & Saha, 2021). Cartographic analysis revealed that 870 blocks are classified under a condition of very severe structural vulnerability, 2,240 in severe structural vulnerability, 1,573 in moderate, 2,254 in low, and 870 blocks are in very low structural vulnerability.

Figure 5. Cartography of structural vulnerability for the municipality of Toluca



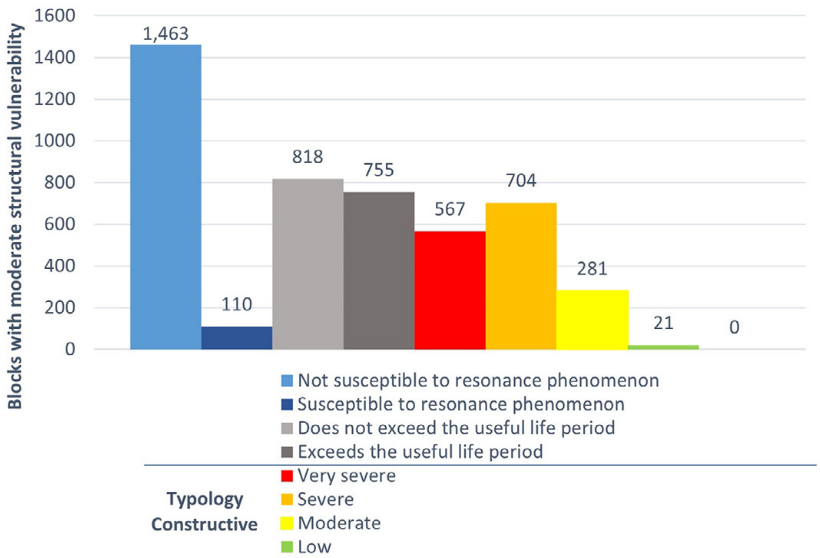

Own elaboration

The blocks with a very severe level of structural vulnerability do not follow a well-defined distribution pattern. Reviewing the attributes in each of the shapes representing the considered indicators indicates that 74.4% of these blocks have exceeded their useful life, according to data from IGECEM (2022a). It is demonstrated that, of the total blocks with a very severe level of structural vulnerability, 100% are prone to seismic resonance, and the three most frequent types of structures were precarious housing (H1), economical housing (H2), and social interest housing (H3).

The blocks classified at the level of severe structural vulnerability are mainly concentrated in the areas of the Toluca de Lerdo neighborhood and other areas in the northern part of the municipality. In these blocks, the most frequent characteristic was the age of the buildings, with 80% of them exceeding the useful life span and being constructed before the enactment of the General Building Regulations of the municipality. Meanwhile, in the northern part of the municipality, the neighborhoods with the most blocks in the category of severe structural vulnerability were San Pablo Autopan (137 blocks) and San Lorenzo Tepatitlán (182 blocks), where the indicator of constructive typology (Precarious housing, H1) influenced significantly.

The level of "moderate" structural vulnerability, representing 20.14% of the blocks. Figure 6 represents the frequency of the three indicators in the 1,573 blocks in the "moderate vulnerability" category.

Figure 6. Influence of seismic resonance, age of buildings, and structure type on the 1,573 blocks classified as having moderate structural vulnerability




Own elaboration

The 2,254 blocks representing low structural vulnerability are notably influenced by 1,218 blocks consisting of social housing structure (H3). It is also noteworthy that 70% of the 2,254 blocks are within the lifespan for which they were designed.

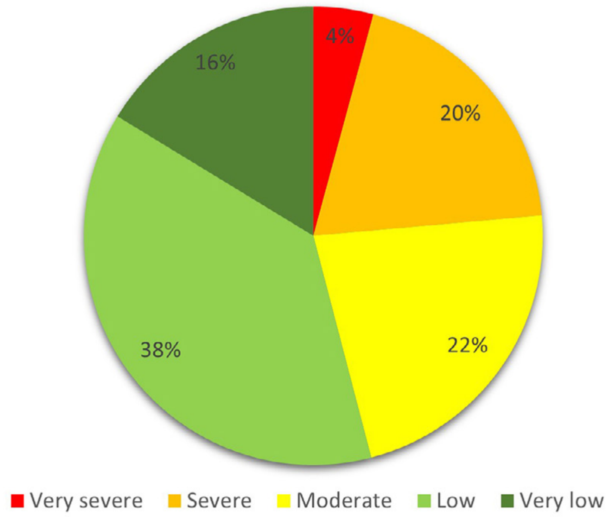
On the other hand, the 870 blocks classified as very low structural vulnerability do not have a defined distribution pattern. The most common characteristics in this level of vulnerability can be summarized as follows: (1) 97.4% of the blocks are within the lifespan for which they were designed, (2) 91.2% of the blocks are located in sites not susceptible to the occurrence of seismic resonance, and (3) none of the 870 blocks, according to the type of structure, fall into the categories of severe or very severe vulnerability.

The analysis of the cartography of structural vulnerability conducted so far indicates priority areas in terms of structural reinforcement measures. Among the components of the seismic risk equation, structural vulnerability is probably the most complex to address due to the substantial economic resources required. However, the spatial analysis of structural vulnerability obtained in this study would support the definition of priority zones for the allocation of resources.

## 3.2. Cartography for socioeconomic vulnerability

The indicators described in section 2.2 allowed the National Population Council of Mexico (CONAPO) to approach critical aspects of the quality of life and socioeconomic conditions of different communities. The cartographic analysis, for the particular case of the municipality of Toluca, revealed that a total of 329 blocks fall into the category of very severe socioeconomic vulnerability. Likewise, 1,512 blocks are in the category of severe socioeconomic vulnerability, 1,745 blocks present a moderate socioeconomic vulnerability, 2,950 blocks have low vulnerability, and 1,271 blocks are in the category of very low socioeconomic vulnerability (Figure 7).

Figure 7. Approach to socioeconomic vulnerability according to CONAPO's (2020a) margination index. The graph expresses the percentage of blocks in each category for 7,807 blocks that make up the municipality of Toluca




Own elaboration

The blocks classified as very severe socioeconomic vulnerability are concentrated north of the urban area, especially in the neighborhoods of Jicaltepec Autopan (94 blocks with this classification), and San Pablo Autopan (108 blocks in this category). The analysis of various indicators shows that the percentage of the population without health insurance affiliation is the characteristic that exerts the greatest influence in this vulnerability category.

The blocks classified in the severe vulnerability category amount to a total of 1,512 (19.4%). These blocks exhibit a unique spatial distribution pattern, predominantly located in the northern zone of the municipality, covering the neighborhoods of La Constitución Totoltepec and San Cristóbal Huichotitlán. Regarding the latter neighborhood, the CONAPO database (2020a) indicates that it has the highest concentration of people with disabilities to go up or down stairs compared to the rest of the municipality. This information is crucial for the objective of the present research. Likewise, with the purpose of validating and quantifying the information, the Census of Population and Housing (INEGI, 2020a) was consulted, which identifies 52 people in this locality with motor disabilities.

The blocks classified in the moderate vulnerability category amount to a total of 1,745, representing 22.3% of the total blocks analyzed. The most influential indicator is the percentage of the population aged 6 to 14 who do not attend school.

The blocks classified as having low and very low socioeconomic vulnerability represent 35% and 17% of the municipal total, respectively, and are spatially located in the center of the municipality. They coincide with areas where urban infrastructure has been consolidated, with the presence of 525 schools (covering all educational levels), 81 sites offering some medical service, 15 government offices, and an extensive network of businesses totaling 208 establishments (National Statistical Directory of Economic Units [DENUE], 2020).

## 3.3. Seismic vulnerability

The seismic vulnerability in the municipality of Toluca is obtained by adding together the structural and socioeconomic vulnerabilities (Figure 8). Both vulnerabilities were standardized between 0 and 1; the sum yielded a minimum of 0.2 and a maximum of 1.8. Stratification is performed using a similar procedure to that employed in estimating structural vulnerability. Table 4 provides a summary of the most frequent characteristics of the five seismic vulnerability (VS) categories. The summary of the most frequent characteristics in each vulnerability category can serve as a guide for local risk management, particularly in the disaster risk reduction stage.

Table 4. Most frequent characteristics according to the seismic vulnerability level

| Level of seismic vulnerability (stratification values) | Number of Blocks | Most frequent characteristics according to the seismic vulnerability level | |
|---|---|---|---|
| | | Structural | Socioeconomic |
| Very low (0.4 – 0.68) | 848 | 3 block exceeds the useful life period. | 99% of the blocks have electricity. |
| | | Only the constructions of eleven blocks are prone to the resonance phenomenon. | 98.2% of children aged 6 to 14 attend school. |
| | | 62.1% of the blocks classify as very low vulnerability according to construction typology. | 79% of people residing in the 848 blocks have affiliation with some type of health insurance. |
| Low (0.69 – 0.96) | 1,462 | 99% of the blocks do not exceed the designed useful life period. | It is relevant that 99.2% of the population aged 6 to 14 attends school. |
| | | Only the structures corresponding to two blocks could suffer the effects of the resonance phenomenon. | |
| Moderate (0.97 – 1.24) | 2,669 | Approximately 40% of the structures exceed the useful life period of their design. | 39% of households in these blocks are classified as overcrowded. |
| | | Structures located in 87% of these blocks probably will not experience resonance in case of an earthquake. | |
| | | 41.4% belong to moderate vulnerability based on construction typology indicator. | |
| Severe (1.25 – 1.52) | 1,852 | Structures located in 69.1% of these blocks have exceeded the useful life period of their original design. | Approximately 33% of the population aged 6 to 14 living in these blocks does not attend school. 16.8% of the homes lack drainage and sanitary facilities, classified by IGECEM (2022b) as precarious housing (H1) and economic housing (H2). |
| | | Structures located in 25.6% of these blocks probably will experience resonance in case of a moderate to severe-magnitude earthquake. | |
| | | 39% of the blocks in this category exhibit very severe vulnerability according to the construction typology indicator. | |
| Very severe (1.53 – 1.8) | 976 | Structures located in 90.5% of these blocks have exceeded the useful life period of their original design. | Approximately 29.5% of the population aged 6 to 14 living in these blocks does not attend school. 21.3% of the homes in blocks with this category lack drainage and sanitary facilities, classified by IGECEM (2022b) as precarious housing (H1) and economic housing (H2). 48.6% of households in these blocks are classified as overcrowded. |
| | | Structures located in 28.9% of these blocks probably will experience resonance in case of a moderate to severe-magnitude earthquake. | |
| | | 76.3% of the 976 blocks in this seismic vulnerability category have homes that belong to structurally fragile construction typologies (H1), generally without foundations and sometimes consisting of adobe walls (IGECEM, 2022b). | |

Own elaboration

Later, .shp files of seismic vulnerability were overlaid with the exposure database (IGECEM, 2022a) and the population census (INEGI, 2020a). This allowed for correlating the most representative neighborhoods with the level of seismic vulnerability, the number of homes, and the population. This approach provides key information for more effective seismic risk management at the municipal level. This exercise was carried out for the levels of moderate, severe, and very severe Vs, as expressed in Table 5, note that the Toluca de Lerdo neighborhood is predominant in the moderate and severe $V_s$ levels.

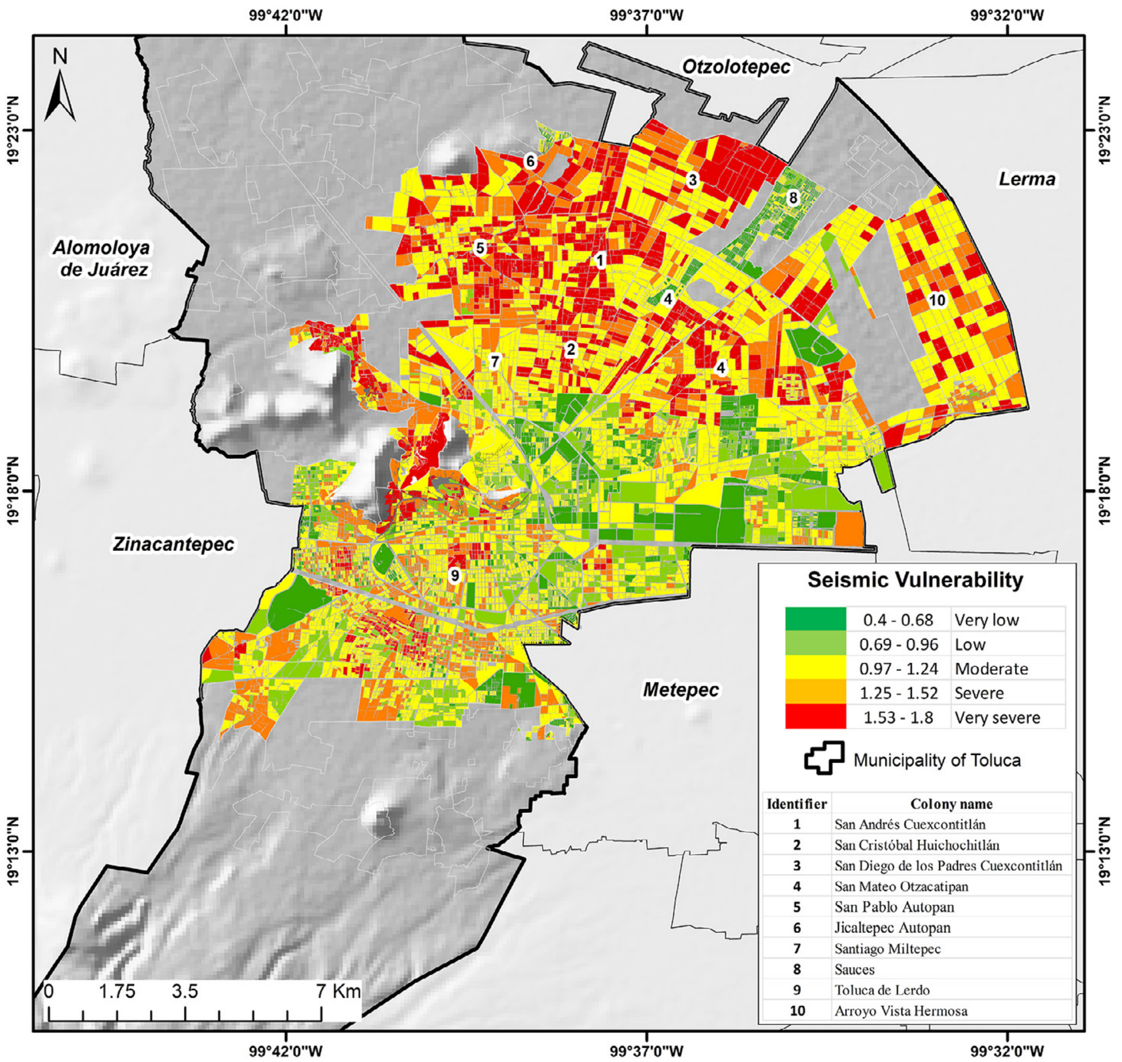
Table 5. Distribution of housing and population in neighborhoods of the municipality of Toluca according to moderate, severe, and very severe levels of seismic vulnerability ($V_s$).

| Seismic vulnerability level | Representative neighborhoods | Number of housing | Population |
|---|---|---|---|
| Moderate | Toluca de Lerdo<br>Sauces<br>Santiago Miltepec | 9,524<br>4,828<br>396 | 43,365<br>11,181<br>3,924 |
| Severe | Toluca de Lerdo<br>San Pablo Autopan<br>San Cristóbal Huichochitlán<br>Jicaltepec Autopan<br>Santiago Miltepec | 27,751<br>2,189<br>2,376<br>2,020<br>1,615 | 120,012<br>18,635<br>20,869<br>10,968<br>8,923 |
| Very severe | Arroyo Vista hermosa<br>San Diego de los Padres Cuexcontitlán<br>San Mateo Otzacatipan<br>San Andrés Cuexcontitlán | 2,051<br>13,025<br>1,210<br>832 | 10,255<br>72,058<br>8,960<br>4,301 |

Own elaboration

This summary highlights the distribution of seismic vulnerability in neighborhoods of the municipality of Toluca de Lerdo, considering the number of homes and the population. It is presented concisely to facilitate understanding of the areas with higher seismic risk and their demographic impact in the region.

Figure 8. Cartography for the distribution of blocks in different ranges of seismic vulnerability in the municipality of Toluca




Own elaboration

## 4. Discussion of results. Seismic vulnerability, local risk management, and development management

Cardona (2023), in his conference "The Future of Risk Management", where he stated:

"The Future of Risk Management is precisely that there is no Risk Management; what should exist is Development Management, where risk management no longer has to be explicitly stated but is already properly incorporated into Development Management".

Certainly, this comment represents a paradigm shift, where the results generated from academia should permeate and be articulated in territorial planning instruments (such as the Municipal Urban Development Plan in the case of Toluca). The results obtained in this study enhance two significant aspects:

(1) Immediately, a path of priorities for disaster risk reduction is outlined, starting from the hypothesis that vulnerability is the only variable in the risk equation that can be influenced. The cartography obtained on the GIS platform and interpreted in this research indicates at the block level where priority attention sites are located and what the focus for the solution (physical or social) would be.

(2) In the very short term, it would enhance the Municipal Urban Development Plan, which would be generated in 2025 (Administration 2025-2027). Specifically, the results obtained here can be considered in the sections of diagnosis, foresight, and strategies. It would justify the allocation of resources for vulnerability reduction.

This research provides a detailed view of vulnerability to seismic risk in the municipality of Toluca, thoroughly addressing 7,807 blocks in a city of approximately 910,608 inhabitants. To integrate the obtained results into risk management processes, at least two concrete actions are proposed from academia before the end of the current year: (a) becoming part of the Advisory Council of the State Coordination of Civil Protection. Currently, the academic space where this research is conducted has two proposed members for the council, and (b) conducting a risk management synergy workshop in September. This event is held every year; for example, in 2023, it was named "Institutional Civil Protection Week". Dissemination spaces are relevant to visualize vulnerability to natural threats and establish areas of opportunity.

This methodology considers variables not only related to construction typologies but also to geology, geotechnical indicators, structural behavior, and socioeconomic indicators. The only similar research for the case study was conducted by Ordaz Hernández et al. (2020), where they worked on 5,121 blocks, excluding 2,686 blocks located mainly in the northern zone of the municipality at that time. The mentioned work focused on the analysis of structural vulnerability, considering construction typology and the age of buildings. However, it did not consider the possible occurrence of the seismic resonance phenomenon.

The seismic risk vulnerability analysis presented in the current proposal can be improved. The authors of this work are currently working on determining institutional vulnerability, where the relevance of government structures and the preparedness of public servants can be assessed. Both governmental structures and the technical personnel within them should enable a robust approach to risk reduction, emergency response, and recovery (the three main stages of disaster risk management).

A second future line of work consists of transitioning from the block scale to the property scale, where the 976 blocks classified in this study with very severe vulnerability to seismic risk will be prioritized in a first stage. At the property scale, details such as plan and vertical irregularities can be defined, similar to the approach taken by García (2015) in the Benito Juárez Delegation of Mexico City. The property-level study could lead to obtaining vulnerability functions for representative buildings in the municipality of Toluca.

Finally, the socioeconomic assessments conducted in this study based on the CONAPO marginalization index constitute a vital input for all three levels of government (municipal, state, and federal). The cartographic result obtained (Figure 4), and its analysis justify the design of consistent governmental actions involving educational programs, expanding employment opportunities, and improving the structural conditions of homes, with a focus on blocks classified as having severe and very severe socioeconomic vulnerability. It is suggested to implement and monitor some of the social programs for poverty alleviation and labor inclusion proposed by the Economic Commission for Latin America and the Caribbean (Abramo et al., 2019). Additionally, efforts can be directed towards participating in projects within the Social Inclusion and Development Program designed by the Inter-American Development Bank (2023).

## 5. Conclusions

The presented work offers a simple and viable alternative to replicate for other municipalities in Mexico. The procedure converges structural and socioeconomic components, with the purpose of obtaining a product of relevance for the subsequent design of Disaster Risk Reduction strategies.

The results obtained are consistent with the level of available information; however, short-term work is needed to: (1) obtain seismic microzonation, (2) strengthen the analysis of structural vulnerability to earthquakes at the municipal level, even with opportunities within empirical methodologies, for example, as applied in Novelo-Casanova & Suárez (2024), (3) transition to the application of analytical methods in the medium term (Milutinovic & Trendafiloski, 2003), and (4) conduct detailed analyses of vulnerabilities in lifelines and heritage buildings.

Specifically, for the municipality of Toluca, the cartography obtained for each of the described indicators, and its integration into a seismic vulnerability map, constitute a tool and roadmap for all levels of government with influence in the municipality. It identifies priority blocks for addressing vulnerability reduction.

## References

Abramo, L., Cecchini, S., & Morales, B. (2019). *Programas Sociales, Superación de la Pobreza e Inclusión Laboral: Lecciones de América Latina y el Caribe*, Libro de la CEPAL, No. 155 (LC/PUB.2019/5-P), Santiago, Comisión Económica para América Latina y el Caribe (CEPAL). https://repositorio.cepal.org/server/api/core/bitstreams/7d9fb18f-1be1-4e0e-9125-0e3de35b5bc7/content

Acevedo, A. B., Jaramillo, J. D., Yepes, C., Silva, V., Osorio, F. A., & Villar, M. (2017). Evaluation of the seismic risk of the unreinforced masonry building stock in Antioquia, Colombia. *Natural Hazards*, *86*(1), 31–54. https://doi.org/10.1007/s11069-016-2647-8

Acevedo, A. B., Yepes-Estrada, C., Gonzalez, D., Silva, V., Mora, M. G., Arcila, M., & Posada, G. (2020). Seismic risk assessment for the residential buildings of the major three cities in Colombia: Bogotá, Medellín, and Cali. *Earthquake Spectra*, *36*, 298–320. https://doi.org/10.1177/8755293020942537

Acuña, J. (2016). Análisis de la Vulnerabilidad Institucional en el Distrito Metropolitano de Caracas. *Terra Nueva Etapa., 13*(52),151-175. https://www.redalyc.org/articulo.oa?id=72148468007

Alas, R. E., & Grijalva, S. O. (2018). *Evaluación de la Vulnerabilidad Sísmica mediante Curvas de Fragilidad, utilizando Análisis Dinámico No Lineal Incremental* [Master's Thesis, Universidad de Salvador]. Repositorio Institucional UES. https://oldri.ues.edu.sv/id/eprint/17633

Alcántara, I., Garza, M., López, A., Magaña, V., Oropeza, O., Puente, S., Rodríguez, D., Lucatello, S., Ruiz, N., Tena, R., Urzúa, M., & Vázquez, G. (2019). Gestión Integral de Riesgo de Desastres en México: reflexiones, retos y propuestas de transformación de la política pública desde la academia. *Investigaciones Geográficas (Mx)*, (98). https://doi.org/10.14350/rig.59784

Armaş, I. (2012). Multi-criteria vulnerability analysis to earthquake hazard of Bucharest, Romania. *Natural Hazards*, *63*(2), 1129–1156. https://doi.org/10.1007/s11069-012-0209-2

Baquedano, P., Ferreira, T. M., Arriagada, C., Sandoval, C., Palazzi, N. C., & Oliveira, D. V. (2023). Multi-vulnerability analysis for seismic risk management in historic city centres: an application to the historic city centre of La Serena, Chile. Natural Hazards, 1-44. https://doi.org/10.1007/s11069-023-06008-8

Bard, P. (1997). Local effects on strong ground motion: basic physical phenomena and estimation methods. *Advanced Study Course on Seismic Risk (SERINA)*, 21-27.

Baró, J. E., & Monroy, F. (2018). *Enfrentando riesgos socio-naturales*. https://www.educacionchiapas.gob.mx/docs/ProteccionCivil/EnfrentandoRiesgosSocionaturales.pdf

Barrantes, G., & Márquez, R. (2011). De la Respuesta ante Desastres a la Gestión del Riesgo: Una Perspectiva Geográfica. *Revista Geográfica de América Central, 2*(47), 15-37. https://www.revistas.una.ac.cr/index.php/geografica/article/view/3966

Bernal, G. H., & Mungaray, A. (2017). Los índices de competitividad en México. *Gestión y Política Pública, XXVI*(1), 167–218. https://www.redalyc.org/articulo.oa?id=13349779005

Buendía, L. M., & Reinoso, E. (2019). Análisis de los Daños en Viviendas y Edificios Comerciales durante el Terremoto del 19 de septiembre de 2017. *Revista de Ingeniería Sísmica, 101*, 19–35. https://doi.org/10.18867/ris.101.508

Burton, C. G., Toquica, M., Asad, K. M. Bin, & Musori, M. (2022). Validation and development of composite indices for measuring vulnerability to earthquakes using a socio-economic perspective. *Natural Hazards*, *111*(2), 1301–1334. https://doi.org/10.1007/s11069-021-05095-9

Cárdenas, X. R. (2021). *Caracterización Estructural y Vulnerabilidad Sísmica de Edificaciones de Adobe* [Doctoral Thesis, Universidad Politécnica de Madrid]. Archivo digital UPM. https://oa.upm.es/67534/1/XAVIER_RICARDO_CARDENAS_HARO_01.pdf

Cardona, O. D. (2001). Estimación holística del riesgo sísmico utilizando sistemas dinámicos complejos [Doctoral Thesis, Universidad Politécnica de Cataluña]. Tesis Doctorals en Xarxa. http://hdl.handle.net/10803/6219

Cardona, O.D. (2023). El futuro de la gestión del riesgo de desastres. In *5º Congreso Internacional sobre Gestión Integral del Riesgo y Resiliencia en Ciudades* (discurso inaugural). https://www.youtube.com/watch?v=mOGT3TiVKqI&t=2231s

Colajanni, P., & D'Anna, J. (2024). Seismic risk assessment of residential buildings by the Heuristic vulnerability model: influence of fragility curve models and inventory scale. *Bul. Earthquake Eng., 22*, 877–910. https://doi.org/10.1007/s10518-023-01801-z

Conlon, K. C., Mallen, E., Gronlund, C. J., Berrocal, V. J., Larsen, L., & O'neill, M. S. (2020). Mapping human vulnerability to extreme heat: A critical assessment of heat vulnerability indices created using principal components analysis. *Environmental Health Perspectives*, *128*(9), 1–14. https://doi.org/10.1289/EHP4030

Cortés, F., & Vargas, D. (2011). Marginación en México a lo largo del tiempo: sobre el índice de Conapo. *Estudios Sociológicos, XXIX*(86), 361–387. https://www.redalyc.org/articulo.oa?id=59823584002

Cui, L., Jing, X., Wang, Y., Huan, Y., Xu, Y., & Zhang, Q. (2023). Improved Swin Transformer-Based Semantic Segmentation of Post earthquake Dense Buildings in Urban Areas Using Remote Sensing Images. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 16, 369–385. https://doi.org/10.1109/JSTARS.2022.3225150

Díaz, S. R., Cadena, E., Adame, S., & Dávila, N. (2020). Landslides in Mexico: their occurrence and social impact since 1935. *Landslides, 17*(2), 379–394. https://doi.org/10.1007/s10346-019-01285-6

Diaz-Segura, E. G. (2017). Incertidumbres en la estimación del periodo fundamental de terrenos inclinados. *Obras y proyectos*, 21, 38-44. https://dx.doi.org/10.4067/S0718-28132017000100005

Dikmen, Ü. (2009). Statistical correlations of shear wave velocity and penetration resistance for soils. *Journal of Geophysics and Engineering*, *6*(1), 61–72. https://doi.org/10.1088/1742-2132/6/1/007

DRAE. (2014) *Diccionario de la Real Academia Española.* https://dle.rae.es/vulnerabilidad

Eboh, H., Gallaher, C., Pingel, T., & Ashley, W. (2021). Risk perception in small island developing states: a case study in the Commonwealth of Dominica. *Natural Hazards, 105*(1), 889–914. https://doi.org/10.1007/s11069-020-04342-9

European Seismological Commission. (2008). *European Macroseismic Scale 1998*. https://web.ua.es/urs/sismosurs/Informes/EMS-98.pdf

Expósito, J. L. (2012). *Características hidrodinámicas e hidroquímicas del acuífero multicapa del Valle de Toluca y sus implicaciones en la optimización de estrategias para la protección de la calidad del agua subterránea*. CIRA, UAEMéx.

Federal District Building Regulations (RCDF). (2004). Código de Construcción de la Ciudad de México. Gobierno de la Ciudad de México.

Federal Electricity Commission (CFE). (2015). Manual de Diseño de Obras Civiles. Sección C: Estructuras. Seguridad Estructural. Capítulo C.1.3. Diseño Sísmico.

Federal Emergency Management Agency (FEMA). (2003). Nehrp Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (Fema 450). *Part 1*, *Fema 450*, 338.

Federal Emergency Management Agency and National Institute of Building Sciences (FEMA/NIBS). (1999). HAZUS' 99 Technical Manual. *Earthquake Loss Estimation Methodology,* 1-3.

García, J. H. (2015). *Evalución de la vulnerabilidad sísmica de edificios urbanos basada en datos geoespaciales* [Master's Thesis, Centro de Investigación Jorge L. Tamayo, A.C.].

Girish, J., Shailesh G., & Piyoosh R. (2019). *Seismic vulnerability of lifeline buildings in Himalayan province of Uttarakhand in India.* https://usdma.uk.gov.in/PDFFiles/Joshi%20et%20al%20IJDRR%202019.pdf

Goded, T. (2010). Evaluación del riesgo sísmico en la ciudad de Málaga. [Doctoral Thesis, Universidad Complutense de Madrid]. https://produccioncientifica.ucm.es/documentos/5d1df61029995204f766030e

González, R., Borraz, P.A., Sánchez A., De la Cruz, Y., Aguilar, J.A., & Ruiz, A. (2010). Construcción histórica de la vulnerabilidad sísmica en Tuxtla Gutiérrez, Chiapas. In *XVII Congreso Nacional de Ingeniería Estructural*.

González, R., Mora, J.C., Aguirre, J., Aguilar, J.A., Paz, J.A., & Moreno, R. (2020). Efectos de sitio en Tuxtla Gutiérrez, Chiapas: Un factor determinante en los daños históricos de edificios. *Ingeniería Sísmica,* (102), 42-64. https://doi.org/10.18867/ris.102.511

Hafidz, H. R., Sarli, P. W., Twinanda, A. P., Santoso, D., & Imran, I. (2024). Building typology classification using convolutional neural networks utilizing multiple ground-level image process for city-scale rapid seismic vulnerability assessment. *Engineering Applications of Artificial Intelligence*, *131*. https://doi.org/10.1016/j.engappai.2023.107824

Hassan, M. M., Elyamani, A., & Mourad, S. A. (2022). Seismic vulnerability assessment of buildings: case study of Al Khalifa district, Fatimid Cairo. *SN Applied Sciences, 4*(11). https://doi.org/10.1007/s42452-022-05192-9

Hoyos, M. C., & Hernández, A. F. (2021). Impact of vulnerability assumptions and input parameters in urban seismic risk assessment. *Bulletin of Earthquake Engineering*, *19*(11), 4407–4434. https://doi.org/10.1007/s10518-021-01140-x

Huang, J., Su, F., & Zhang, P. (2015). Measuring social vulnerability to natural hazards in Beijing-Tianjin-Hebei Region, China. *Chinese Geographical Science*, *25*(4), 472–485. https://doi.org/10.1007/s11769-015-0769-7

Iglesias Asenjo, S., Irigaray Fernández, C., & Chacón Montero, J. (2006). Analysis of Seismic Risk in Urban Areas Using Geographic Information Systems. Application to the City of Granada. *Cuadernos Geográficos*, (39), 147-166.

Iglesias-Lesaga, E., & Carmona-Motolinia, J. R. (2016). Inequidades, territorios y vulnerabilidades en el desarrollo de América Latina (1990-2015). *Sociedad y Economía*.*31*, 123–148. https://doi.org/10.25100/sye.v0i31.3891

Institute of Geographic, Statistical and Cadastral Information and Research of the State of Mexico (IGECEM). (2022a). *Datos sobre el comportamiento de los edificios del municipio de Toluca por propiedad. Datos inéditos.*

Institute of Geographic, Statistical and Cadastral Information and Research of the State of Mexico (IGECEM). (2022b). Manual Catastral del Estado de México 2022. Gobierno del Estado de México. *Secretaría de Finanzas - Instituto de Información Geográfica, Estadística y Catastral e Investigación del Estado de México.* 5–256. https://igecem.edomex.gob.mx/sites/igecem.edomex.gob.mx/files/files/ArchivosPDF/Servicios-catastrales/Manual%20Catastral%20del%20Estado%20de%20Mexico.pdf

Inter-American Development Bank (2023). *Inclusion and Social Development Program.* https://www.iadb.org/es/whats-our-impact/PN-L1105

Jaimes, D. L., Escudero, C. R., Flores, K. L., & Zamora-Camacho, A. (2023). Multicriteria seismic hazard and social vulnerability assessment in the Puerto Vallarta metropolitan area, Mexico: toward a comprehensive seismic risk analysis. *Natural Hazards, 116*(2), 2671–2692. https://doi.org/10.1007/s11069-022-05783-0

Lee, S., & Oh, S. (2022). A comprehensive seismic risk assessment map of South Korea based on seismic, geotechnical, and social vulnerability. *Environmental Earth Sciences*, *81*(1). https://doi.org/10.1007/s12665-021-10153-3

Li, S. Q., & Formisano, A. (2023). Updated empirical vulnerability model considering the seismic damage of typical structures. *Bulletin of Earthquake Engineering, 22, 1147-1185.* https://doi.org/10.1007/s10518-023-01814-8

Martins, L., & Silva, V. (2021). Development of a fragility and vulnerability model for global seismic risk analyses. *Bulletin of Earthquake Engineering*, *19*(15), 6719–6745. https://doi.org/10.1007/s10518-020-00885-1

Meyers-Angulo, J. E., Martínez-Cuevas, S., & Gaspar-Escribano, J. M. (2023). Classifying buildings according to seismic vulnerability using Cluster-ANN techniques: application to the city of Murcia, Spain. *Bulletin of Earthquake Engineering, 21*(7), 3581–3622. https://doi.org/10.1007/s10518-023-01671-5

Milutinovic, Z. V. and Trendafiloski, G. S. (2003). WP4. *Vulnerability of current buildings. RISK-UE project: An advanced approach to earthquake risk scenarios with applications to different European towns.* Institute of Earthquakes Engineering and Engineering Seismology (IZIIS).

Ministry of Agrarian, Territorial, and Urban Development (SEDATU). (2020). *MGN 2020 Municipio. Gobierno de México: Desarrollo Territorial*. https://www.gob.mx/sedatu/documentos/metropolis-de-mexico-2020?state=published

Molina, S., Lang D.H, & Lindholm, C.D. (2010). SELENA – Na open-source-tool for seismic risk and loss assessment using a logic tree computation procedure. *Computers & Geosciences*, 36, 257-269. https://doi.org/10.1016/j.cageo.2009.07.006

Municipal Government of Toluca (1993). *Reglamento General de Construcciones del Municipio de Toluca.* Honorable Ayuntamiento de Toluca.

Muñoz-Sánchez, M. L. (2019). Análisis de la Vulnerabilidad Institucional en la Ciudad de Tunja: Un Enfoque para la Gestión de Desastres Naturales [Engineering Thesis, Universidad Santo Tomás]. Repositorio Institucional Universidad Santo Tomás. https://repository.usta.edu.co/handle/11634/19002?show=full

National Earthquake Hazards Reduction Program (NEHRP). (1994). *Nehrp Recommended Provisions For Seismic Regulations For New Buildings Part 1-Provisions Issued by FEMA in furtherance of the Decade for Natural Disaster Reduction*.

National Institute of Buildings Sciences (NIBS). (2000). https://wbdg.org/FFC/NIBS/nibs_asbestos_specs.pdf

National Institute of Statistics and Geography (INEGI). (2010). *Censo de Población y Vivienda 2010*. https://www.Inegi.Org.Mx/Rnm/Index.Php/Catalog/71

National Institute of Statistics and Geography (INEGI) (2020a). *Censo de Población y Vivienda 2020*. https://www.inegi.org.mx/programas/ccpv/2020/#Datos_abiertos

National Institute of Statistics and Geography (INEGI) (2020b). *Población total a nivel manzana* INEGI Digital Map v.6.3.0. https://www.inegi.org.mx/temas/mg/#Metadatos

National Population Council of Mexico (CONAPO). (2020a). *Mapeo digital (shp) del índice de marginalización urbanaporcolonia2020.* https://www.gob.mx/conapo/documentos/indices-de-marginacion-2020-284372

National Population Council of Mexico (CONAPO). (2020b). *El índice de Marginalización Urbana 2020.* https://www.gob.mx/cms/uploads/attachment/file/828844/urbana.pdf

National Statistical Directory of Economic Units (DENUE). (2020, Enero). *Directorio de empresas y establecimientos. Directorio de Empresas y Establecimientos del Estado de México.*

Novelo-Casanova, D. A., & Suárez, G. (2024). Social and seismic structural vulnerability in Zihuatanejo, Guerrero, Mexico. *Natural Hazards,* 120, 4925-4939. https://doi.org/10.1007/s11069-023-06385-0

Olcina, J. (2022). Land Use Planning and Green Infrastructure: Tools for Natural Hazards Reduction. In S. Eslamian & F. Eslamian (Eds.), *Disaster Risk Reduction for Resilience: Disaster Risk Management Strategies* (pp. 129–146). Springer International Publishing. https://doi.org/10.1007/978-3-030-72196-1_6

Oliveira, C. S., & Navarro, M. (2010). Fundamental periods of vibration of RC buildings in Portugal from in-situ experimental and numerical techniques. *Bulletin of Earthquake Engineering*, *8*(3), 609–642. https://doi.org/10.1007/s10518-009-9162-1

Ordaz Hernández, A., Hernández Millán, J. A., & Garatachia Ramírez, J. C. (2020). Aproximación cartográfica a la vulnerabilidad estructural ante sismos empleando una metodología cualitativa: aplicación para la Ciudad de Toluca. *Cuadernos Geográficos, 59*(2), 178–198. https://doi.org/10.30827/cuadgeo.v59i2.9340

Ordaz Hernández, A. (2022). Aproximación Cartográfica a la Respuesta Sísmica Local en la Ciudad de Toluca, México: Una Contribución a la Reducción de Riesgos de Desastres. *Revista de Estudios Latinoamericanos sobre Reducción del Riesgo de Desastres REDER*, *6*(2), 60-71. http://doi.org/10.55467/reder.v6i2.97

Orozco, V., & Reinoso, E. (2007). A 50-year review of the damage caused in Mexico City by the earthquake of July 28, 1957 with the help of recent research and geographic information systems. *Journal of Earthquake Engineering*, *76*, 61–87. https://doi.org/10.18867/ris.76.131

Parajuli, R. R. (2020). Citizen disaster science education for effective disaster risk reduction in developing countries. *Geoenvironmental Disasters*, *7*(1), 1–4. https://doi.org/10.1186/s40677-020-00150-2

Peláez, O. (2023). "El Índice de Marginación del CONAPO transformado en un indicador cardinal: 50 años de marginalización comparados en el tiempo. *EconoQuantum*, *20*(1), 59–82. https://www.redalyc.org/articulo.oa?id=125075173003

Pérez-Morente, M. Á., Sánchez-Ocón, M. T., Martínez-García, E., Jiménez Bautista, F., & Hueso-Montoro, C. (2017). Crisis económica, políticas sociales y desigualdades en salud. *Revista de Paz y Conflictos, 10*(2), 207-232.https://www.redalyc.org/articulo.oa?id=205054523010

Ramírez, H., Vera, R., Rivera, J. L., Pérez, J. & Manjarrez, L. (2002). Propuesta de Reglamento de Construcción para el Municipio de Toluca. In *XIII Congreso Nacional de Ingeniería Estructural de la Sociedad Mexicana de Ingeniería Estructural*.

Ramírez, T. & Lugo, J. (2000). Efectos del terremoto de magnitud 7.0 en la escala de Richter del 15 de junio de 1999 en Puebla y estados vecinos. *Investigaciones Geográficas (Mx),* (43), 32-41.

Ramos, D. (2019). Entendiendo la vulnerabilidad social: una mirada desde sus principales teóricos. *Estudios del Desarrollo Social: Cuba y América Latina*, 7(1), 139-153. https://www.redalyc.org/articulo.oa?id=552364016005

Razo, D. G., & Domínguez, O. G. (2020). Evaluación Integral de la Seguridad Estructural de Edificios Existentes Dañados por Grandes Terremotos. *Journal of Earthquake Engineering*, 104, 51–71. https://doi.org/10.18867/ris.104.565

Rocabado, V., Schmitz, M., Hernández, J. J., & Morales, C. (2011). Relación entre el período del suelo y la profundidad del sedimento para la ciudad de Caracas, Venezuela. *Revista de La Facultad de Ingeniería Universidad Central de Venezuela, 26, 141–152.*

Ruiz, A., Vidal, F., & Aranda, C. (2016). Estudio de la Vulnerabilidad Sísmica del Centro Histórico de Tapachula, Chiapas, con el Método del Índice de Vulnerabilidad. *Desastres Naturales, Accidentes e Infraestructura Civil, 15*(1). https://core.ac.uk/download/pdf/296529503.pdf

Saha, A., & Saha, S. (2021). Application of statistical probabilistic methods in landslide susceptibility assessment in Kurseong and its surrounding area of Darjeeling Himalayan, India: RS-GIS approach. *Environment, Development and Sustainability, 23*(3), 4453–4483. https://doi.org/10.1007/s10668-020-00783-1

Sallam, M. A., Hassan, H. M., Sayed, M. A., Abdel Hafiez, H. E., Zahra, H. S., & Salem, M. (2023). Seismic vulnerability assessment of historical minarets in Cairo. *Geoenvironmental Disasters, 10*(1). https://doi.org/10.1186/s40677-023-00260-7

Sánchez F., Ordaz A., Baró J. E. y Balderas M. Á. (2022). Cartografía de la respuesta sísmica local: una contribución a la gestión del riesgo en la zona metropolitana del Valle de Toluca. *Anales de Geografía de la Universidad Complutense*, *42*(2), 509-531. https://doi.org/10.5209/aguc.85182

Serrano, B., & Temes, R. (2015). Vulnerabilidad y riesgo sísmico de los edificios residenciales estudiados dentro del Plan Especial de evaluación del riesgo sísmico en la Comunidad Valenciana. *Informes de la Construcción, 67*(539), e104, http://dx.doi.org/10.3989/ic.13.182

Sol de Toluca. (2022). *Mercado 16 de Septiembre en Toluca con daños estructurales.* https://www.elsoldetoluca.com.mx/local/sismo-edomex-mercado-16-de-septiembre-de-toluca-con-danos-estructurales-7942161.html

Tatano, H., Collins, A., & James, W. (2023). Report on the 4th Global Summit of Research Institutes for Disaster Risk Reduction (4thGSRIDRR2019). In H. Tatano & A. Collins (Eds.), *Proceedings of the 4th Global Summit of Research Institutes for Disaster Risk Reduction* (pp. 3–90). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-5566-2_1

Tena-Colunga, A., Hernández-Ramírez, H., Godínez-Domínguez, E. A., Pérez-Rocha, L. E., Grande-Vega, A., & Urbina-Californias, L. A. (2021). Seismic behavior of buildings in Mexico City during the 2017 Puebla–Morelos earthquake. *Asian Journal of Civil Engineering, 22*(4), 649–675. https://doi.org/10.1007/s42107-020-00338-9

Tinoco, T., Cotos, J., & Bayona, R. (2019). Evaluación de la Vulnerabilidad Sísmica de Edificios en el Área Urbana del Distrito de Chiquián, Utilizando el Constructor de Modelos de ArcGIS. *Aporte. Santiaguino, 11(2),* 263–274. https://doi.org/10.32911/as.2018.v11.n2.580

Vargas, Y. F., Pujades, L., Barbat, A. H., & Hurtado, J. E. A. (2013). Evaluación probabilística de capacidad, fragilidad y daño sísmico de edificios de hormigón armado. *Revista Internacional de Métodos Numéricos para el Cálculo y Diseño en Ingeniería*, *29*, 63–78. https://doi.org/10.1016/j.rimni.2013.04.003

Zúñiga, F. R., Suárez, G., Figueroa-Soto, Á., & Mendoza, A. (2017). A first-order seismotectonic regionalization of Mexico for seismic hazard and risk estimation. *Journal of Seismology*, *21*(6), 1295–1322. https://doi.org/10.1007/s10950-017-9666-0