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ORIGINAL PAPER

Social and seismic structural vulnerability in Zihuatanejo, Guerrero, Mexico

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Abstract

The spatial distribution of the social and seismic structural vulnerabilities in Zihuatanejo (ZIH), Guerrero, Mexico, was estimated. Social vulnerability was assessed considering twelve indicators, including parameters such as access to health services, education, housing, employment, and unfavorable family conditions. Seismic structural vulnerability was evaluated characterizing the structural features of local houses, assessing the type and age of construction, and the quality of building materials. Surveyed households were randomly selected from a statistically significant sample. Our findings indicate that in the western and eastern areas of ZIH the population has high and very high social vulnerability. The main factors that condition these levels of social vulnerability are low-income, female-headed families, and households with marginal access to information technology, such as internet and telephone. Although seismic ground amplification in ZIH is relatively low, the regions to the west and southwest of the city are zones where the impact of strong earthquakes to constructions may be greater than in other areas. In particular, the districts of Lázaro Cárdenas, Benito Juárez, Cuauhtémoc, Emiliano Zapata, Las Mesas, Buenos Aires, Lomas del Quebrachal, and Lomas del Riscal would be affected. In general, houses vulnerable to the impact of earthquakes are in regions where the population is socially more vulnerable. More than 50% of the population and 30% of the houses have high and very high level of social and structural vulnerability, respectively. Our results provide information to the local and federal authorities to strengthen their civil protection and mitigation plans.

Keywords Social vulnerability · Structural vulnerability · Vulnerability assessment · Risk assessment · Zihuatanejo · Mexico

1 Introduction

Hazard is considered as the probability of occurrence of a natural or man-made event with the potential to damage an exposed population and its infrastructure. Vulnerability is determined by the social, economic, physical, and environmental characteristics of a community

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that make it susceptible to be damaged by a hazard. It is difficult to measure vulnerability because it is independent of the magnitude and/or intensity of the disturbing event (Rashed and Weeks 2003). Risk assessment requires the evaluation of the different hazards and the vulnerability level of the exposed community. Thus, risk is the probability of expected damage that a perilous event (natural or man-made) would have on a given locality (Cutter et al. 2003).

In this work, we analyze the spatial distribution of the social and structural vulnerabilities of dwellings in the community of Zihuantanejo (ZIH) Guerrero, Mexico. As in Novelo-Casanova et al. (2019), we measure the levels of structural vulnerability by evaluating the design, geometry, materials used for construction, and the number of stories, among other factors, that make a construction susceptible to be damaged by large earthquakes. We applied the methodology of Novelo-Casanova et al. (2022) to determine the spatial distribution of the social vulnerability considering twelve indicators from health, education, housing, and employment sectors. Also, we analyzed variables that make a household vulnerable under unfavorable family conditions.

ZIH lies on the Pacific coast of Mexico, along the subduction zone that marks the boundary between the Cocos and Rivera plates (Fig. 1). Due to this tectonic situation, ZIH is exposed to the impact of large earthquakes. In recent years, the city was affected by three subduction earthquakes: the 14 March 1979 Petatlan (M_w 7.6), the 19 (M_w 8.1) and the 21 September (M_w 7.6) 1985 Michoacan earthquakes (Fig. 1). In addition to these events, there are intraplate earthquakes that occur within the subducted Cocos plate. The latest example in the vicinity of ZIH is the 10 December 1994 (M_w 6.6) earthquake (Cocco et al.

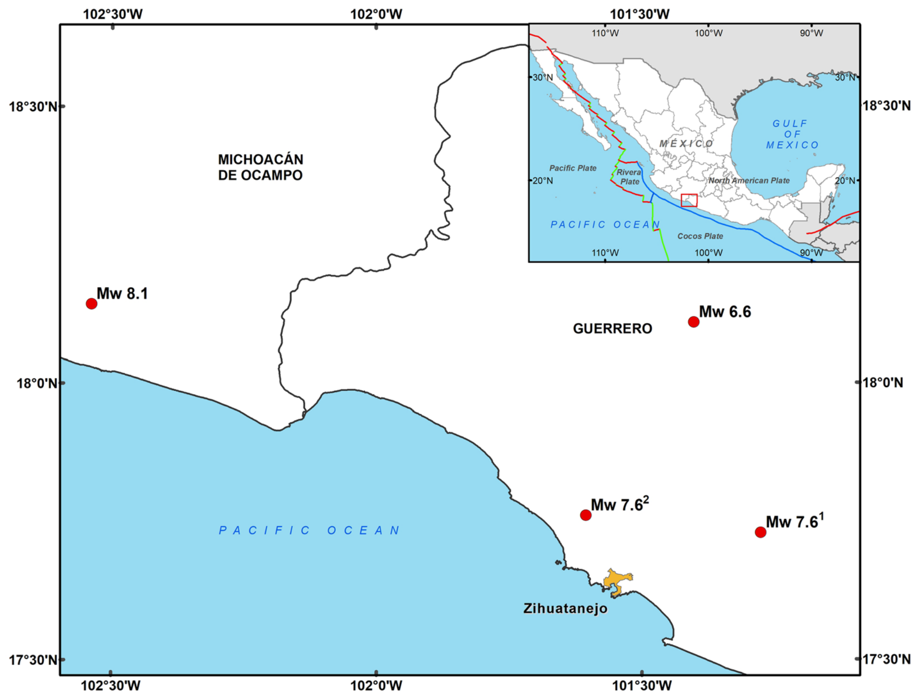

Fig. 1 Geographical location of Zihuatanejo and epicenters of the 10 December 1994 (M_w 6.6), 14 March 1979 (M_w 7.6[1]), and the 19 (M_w 8.1) and 21 September (M_w 7.6.[2]) 1985 earthquakes (http://www.isc.ac.uk)

1997). The coast of Zihuatanejo lies to the south of the devastating earthquake of 19 September 1985, in what is considered a seismic gap, where large earthquakes ($M_w > 8$) have not occurred for several decades (Singh et al. 1981; Nishenko and Singh 1987; Anderson et al. 1989; Kostoglodov and Ponce 1994).

Although in the instrumental record no earthquakes larger than M_w 8.1 have occurred near ZIH, Suárez and Albini (2009) suggested that historical records show the presence of great subduction earthquakes ($M_w > 8.6$) in the Mexican subduction zone. Plata-Martínez et al. (2021) suggested that an earthquake $M_w > 8$ with epicenter in the Guerrero seismic gap would be capable of producing a catastrophic tsunami impacting coastal communities, including Acapulco and ZIH, among others. One of the larger tsunamis in Mexico during the twentieth century had a maximum height of 11 m on the Port of Zihuatanejo. Some authors suggested that it was generated by the 16 November 1925 earthquake (M_s 7.0), located about 600 km from ZIH (Iida et al. 1967; Sanchez and Farreras 1993). However, Singh et al. (1998) showed that there is no evidence of a local earthquake near ZIH responsible for the tsunami. Singh et al. (1998) suspect that it was probably due to slumping of the sea floor near ZIH. More recently, the great 19 September 1985 seismic event ($M_w = 8.1$) also generated a tsunami that impacted ZIH (3 m height) (Singh et al. 1998).

According to the Mexican National Housing Census of 2020 (MCPH20) of the National Institute of Statistics and Geography (Instituto Nacional de Estadística y Geografía in Spanish), ZIH had a population of 126,001 inhabitants (https://www.inegi.org.mx/app/scitel/Default?ev=9). This is a dramatic increase from the 17,873 people who lived in ZIH in 1970. The large increase in population in the past decades and the location of the city in an area of high exposure to extreme natural phenomena, were the incentives to conduct this work. We consider that it is important to assess the potential social and structural consequences of the occurrence of a large earthquake impacting this community. The objective is to provide measurable evidence of the social and structural vulnerability for local and federal authorities, in the hope that it may serve to improve civil defense measures and hazard mitigation programs.

2 Methodology

2.1 Methodology to estimate social vulnerability

Step 1. A preliminary assessment of the spatial distribution of the social vulnerability in ZIH was obtained using data from the MCPH20. We considered twelve weighed social variables following the methodology of Novelo-Casanova et al. (2022). These variables include data of health, education, housing, employment, and unfavorable family conditions that make a dwelling susceptible to be damaged by the impact of an earthquake (Table 1).

The MCPH20 provides data from the census report averaged at the level of city blocks. Thus, for this preliminary assessment of the social vulnerability, we used the information available for the 1847 blocks of ZIH's urban area. Data processing was performed using the ArcGIS 10.2 Field Calculator Tool and the block shapefile of ZIH.

Step 2. During October and November 2021, fieldwork was carried out in ZIH to collect the twelve social vulnerability indicators considered in this study (Table 1). Using the methodology of Novelo-Casanova and Rodríguez-Vangort (2016), a statistically significant sample of houses was determined. Considering the number of lots ($N = 24{,}739$), the minimum survey sample (n) should be at least 360 dwellings. Based on this result, 370

Table 1 Indicators and weights used to assess social vulnerability

Indicator	Description	Weighing (w_i)
SV_1	*Health*	0.079
	Percentage of population with access to public or private health services	
SV_2	*Education and Knowledge*	0.088
	Percentage of illiteracy for persons 15 years old and older	
SV_3	Percentage of population between 6 and 14 years old that do not attend school	0.074
SV_4	Percentage of houses with devices or technology for accessing information	0.123
SV_5	Level of education	0.119
SV_6	*Housing*	0.131
	Percentage of housing without basic services	
SV_7	Percentage of houses with dirt floor	0.064
SV_8	Average of number of family members/ number of rooms)	0.096
SV_9	*Employment*	0.046
	Economic dependency ratio	
	Unfavorable family conditions	
SV_{10}	Percentage of indigenous-speaking population	0.061
SV_{11}	Percentage of population with disabilities	0.084
SV_{12}	Percentage of female-headed households	0.034

families were surveyed using the simple random sampling technique (Yates et al. 2008) to estimate the spatial distribution of social vulnerability in ZIH. During our fieldwork, all interviews to the families of the selected houses were structured using a standard questionnaire designed to glean the information of the social indicators. In addition, we performed on-site housing visual inspections.

The social vulnerability for each family house (SV_h) was estimated as follows using the social indicators (SV_i) and their weights (w_i) (Table 1; Novelo-Casanova 2022):

$$\mathrm{SV}_{h=1\ldots370} = \sum_{i=1}^{12} \mathrm{SV}_i * wi \tag{1}$$

To map the spatial distribution of social vulnerability, the SV_h values from Eq. (1) were interpolated using a Kriging method. The raster distribution obtained was classified in five classes using the Natural Breaks process of the ArcGIS10.2 (Jenks 1967): Very Low, Low, Moderate, High, and Very High.

As in Step 1, the processing of the indicators was carried out with the software ArcGIS 10.2 and the tool Field Calculator for each of the 370 houses considered. Indicators 5, 8, and 9 are not expressed in percentages, therefore, the 12 indicators were normalized.

2.2 Methodology to estimate seismic structural vulnerability

A total of 406 houses were selected randomly to determine the spatial distribution of seismic structural vulnerability in ZIH. This number is larger than the minimum sample of 360 dwellings, determined statistically. This was done to include a larger number of construction types. This assessment was carried out by estimating a Seismic Index for Housing

Typology (SI) to each analyzed dwelling (Reyes-Salinas et al. 2004; Novelo-Casanova et al. 2019). To this end, field work was carried out to obtain data based on questionnaires and on-site housing visual inspections. As in Reyes-Salinas et al. (2004) and Novelo-Casanova et al. (2019), the houses surveyed were classified in ten typologies from 1 to 10, according to the characteristics and type of material used for construction, including the foundations, walls, and roof. Also, other quality indicators were considered such as structural type, age, and property value. A numerical value of $SI=1$ is assigned to the house typology that is considered to better resist the impact of an earthquake; number 4 corresponds to the more vulnerable houses (Table 2; Novelo-Casanova et al. 2019).

The Seismic Structural Vulnerability Index (SVI) was estimated from the following equation (Reyes-Salinas et al. 2004):

$$SVI_i = \frac{SI_i SH_i}{SI_W SH_M} \tag{2}$$

where:

SVI_i = Seismic structural vulnerability index for house *i*.

SI_i = Seismic housing damage index for house *i* according to Table 2.

SI_w = Highest *SI* value obtained in the study area (in this case = 3.2).

SH_i = Peak ground acceleration (PGA) according to property location. To quantify this parameter, we located each property in the seismic microzonation map of Zihuatanejo obtained in a previous project (Fig. 2). Zone I = 0.08, Zone II = 0.14.

SH_M = Highest PGA identified in the study area (0.80).

The value of SH_M was obtained from the seismic design spectrum with an exceedance probability of 500 years developed by the Mexican Power Company (CFE) in 1993 (Novelo-Casanova et al. 2019).

The spatial distribution of *SVI* was mapped using the same procedures as in the case of the social vulnerability assessment and classifying the results in five categories:

- Very low: Unlikely damage
- Low: Minor damage
- Moderate: Moderate damage
- High: Significant damage
- Very high: Severe damage

3 Results

3.1 Results of the social vulnerability

The preliminary social vulnerability estimation obtained in Step 1 of our methodology, evaluated at the city block level, shows zones where low and high vulnerability is expected (Fig. 3). The results show that in the eastern and western parts of the city, social vulnerability is high or very high. Also, an elongated region with high vulnerability was identified to the southeast of the urban area (Fig. 3). Based on these preliminary findings, we focused our fieldworks following Step 2 of our methodological procedures.

The data collected in ZIH during the months of October and November 2021 allowed us to identify with greater detail the spatial distribution of the social vulnerability of ZIH dwellings. In the survey conducted in the selected sample, we found that, although

Table 2 Housing typology and Seismic Housing Damage Index (Modified from Reyes-Salinas et al. 2004; Novelo-Casanova et al. 2019)

Typology	Characteristics	*SI*	Picture
1	Walls of reinforced stone masonry. Rigid roof and foundation of concrete Height: one to five floors	1.0	
2	Walls of reinforced stone masonry. Rigid roof and foundation of masonry Height: one floor	1.5	
3	Walls inefficiently reinforced, rigid roof and foundation of stone masonry Height: one to two floors	2.0	
4	Walls poorly reinforced, flexible roof and foundation of stone masonry Height: one floor	2.2	
5	Walls without reinforcement, rigid roof and foundation of stone masonry Height: one to three floors	3.2	

Table 2 (continued)

Typology	Characteristics	*SI*	Picture
6	Walls without reinforcement, flexible roof and foundation of stone masonry Height: one floor	3.0	
7	Walls of adobe with rigid roof and foundation of stone masonry Height: one to two floors	3.6	
8	Walls of adobe with flexible roof and foundation of stone masonry Height: one floor	4.0	
9	Walls of wood structure and flexible corrugated roof sheeting. Foundation of stone masonry Height: one floor	2.5	
10	Walls and roof built with flexible material. Foundation of stone masonry Height: one floor	2.7	

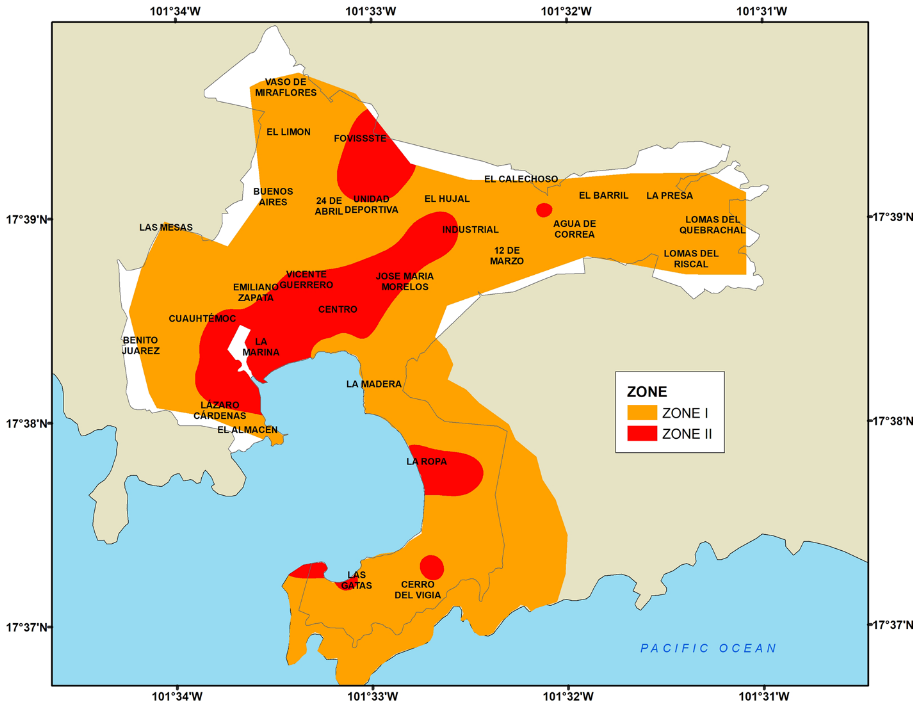

Fig. 2 Seismic microzonation of Zihuatanejo, Guerrero. Zone I is mainly hard rock. Zone II is composed of hard and soft rock. Modified from (GEOEXPLORA 2021)

the areas with high or very high vulnerability are like those obtained from Step 1 of our methodology, the actual extension of these zones has a larger areal than the one observed in the preliminary analysis and covers about one-third of ZIH's territory (Fig. 4).

We consider that the spatial distribution of social vulnerability assessed from the house-to-house visits is more accurate than the one obtained from the MCPH20 data, because the census information is averaged at the city block level, whereas the fieldwork data were gathered from individual household visits. Therefore, we consider that the spatial distribution of the social vulnerability determined from the sampled houses is a more reliable estimate. The results are as follows:

Very Low–Low social vulnerability. About 33% of the city has this level of vulnerability. It is mainly concentrated in the central part of ZIH. In this zone, the socioeconomic conditions are above average compared to other local sites (Fig. 4). Most of the hotels and other tourist facilities in ZIH are concentrated here. This zone is considered as a residential-commercial zone.

Moderate social vulnerability. ZIH shows moderate social vulnerability to the east and west of its territory. Also, some areas near the coast have this level of vulnerability, where some tourism infrastructure is located (Fig. 4). In these zones there is a great diversity of families with different levels of socioeconomic conditions. Also, these parts of the city concentrate most of the population of ZIH with low to high levels of urban marginalization. Besides, most houses and infrastructure have regular to good structural conditions.

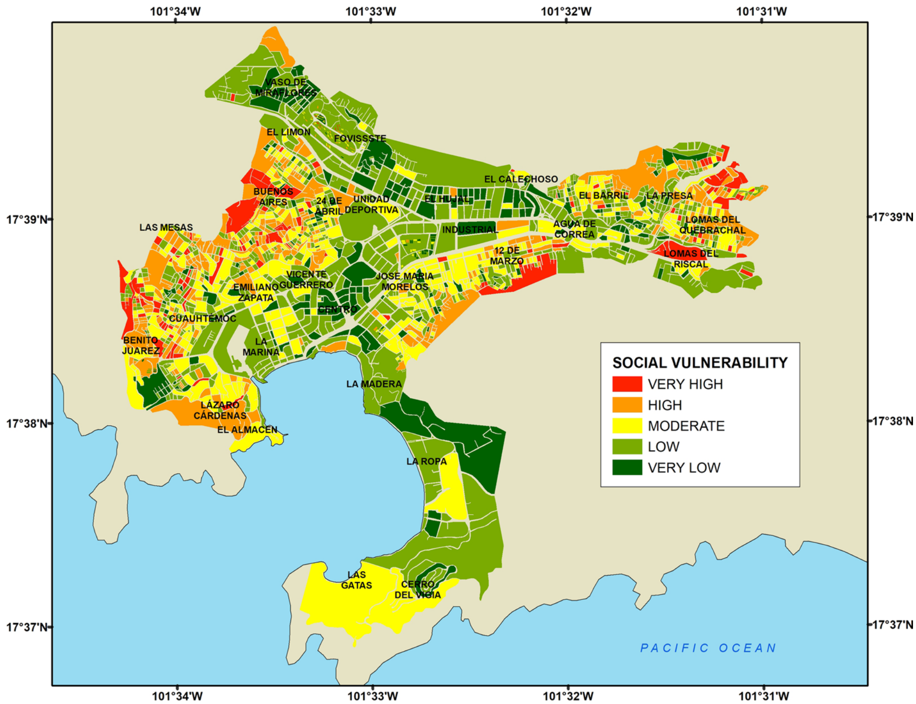

Fig. 3 Spatial distribution of the preliminary social vulnerability analysis (Step 1 of our methodology), using data at the city block level (light-brown lines within the town) from the Mexican Census of Population and Housing 2020 (see text)

High–Very High social vulnerability. They are zones concentrated in the eastern and western periphery of the city (Fig. 4). Zones with this high–very high level of social vulnerability cover about 33% of the ZIH territory. Most of these areas have high level of social marginalization. This area is dominated by irregular settlements, high levels of unemployment, low education, insufficient health, and public services, as well as houses in precarious conditions. We found that the indicators that predominantly condition this level of vulnerability are those low-income families headed by single females and households with marginal access to information technology (internet, computer, telephone, etc.). Clearly, these regions should be the priority of local authorities to implement programs aimed at reducing their level of vulnerability and risk.

3.2 Results of the structural vulnerability

The highest *SI* values reflecting dwellings with high structural vulnerability are concentrated in the western and eastern parts of the city and to the southwest of ZIH (Fig. 5). Not surprisingly, the high values of structural vulnerability coincide with areas of high or very high social vulnerability (Fig. 4). Houses with a typology susceptible to be damaged by the impact of an earthquake are in regions where the population is socially more vulnerable. The most exposed districts are Lázaro Cárdenas, Benito Juárez, Cuauhtémoc, Emiliano Zapata, Las Mesas, Buenos Aires, Lomas del Quebrachal, and Lomas del Riscal (Fig. 5).

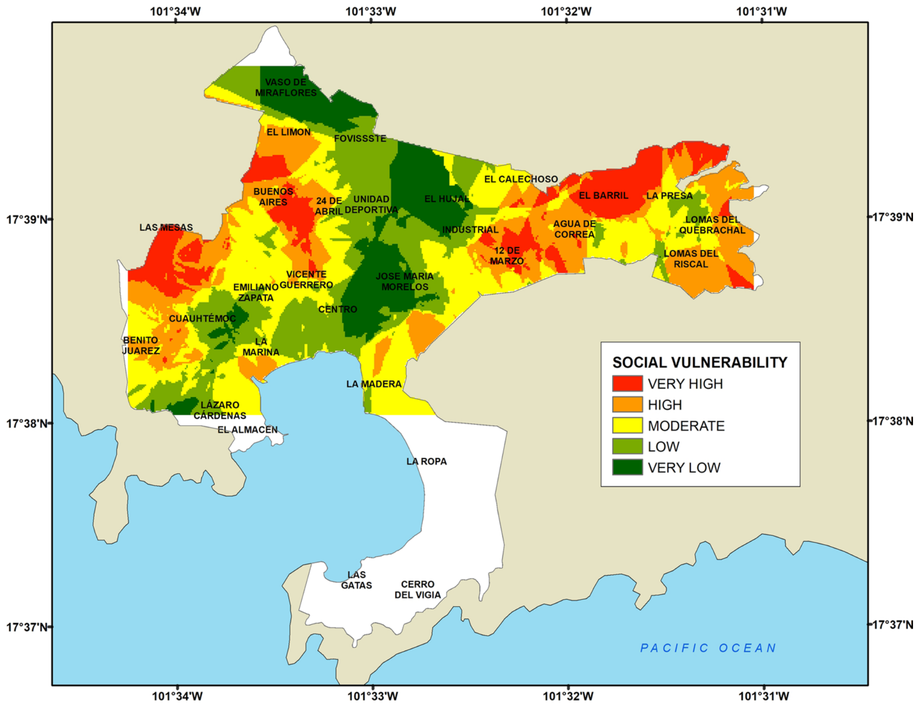

Fig. 4 Spatial distribution of social vulnerability obtained from fieldwork data in ZIH (Step 2 of our methodology). The white areas located to the north, south, and northwest of the city were not considered in this assessment because in these zones the owners of the few houses were unwilling to participate in the project

In contrast, the areas showing relatively low levels of structural vulnerability are, in general, regions of the city where social vulnerability is also low. The residential constructions in these zones are in relatively good condition. It is also where many tourist hotels are located.

4 Discussion of the results

More than 50% of the population of ZIH is subjected to a high or very high level of social vulnerability. Our findings identify the differential susceptibility of the ZIH population to disaster impact. Measurement of the level of social vulnerability is an essential component for the development of a proper disaster-risk reduction strategy (Birkmann 2006; Ignacio et al. 2016). High social vulnerability decreases the resilience of communities in disaster situations because socially vulnerable populations are more likely to be severely affected (Flanagan 2011). Drakes et al. (2021) recommend considering social vulnerability in short-term disaster assistance programs.

Our results show that one of the main factors that accentuate social vulnerability in ZIH are households headed by single females. Most of these families are especially vulnerable because, in addition to their low income, these family nuclei usually take care of their children and elders, the populations that are more vulnerable in disastrous events (Flanagan

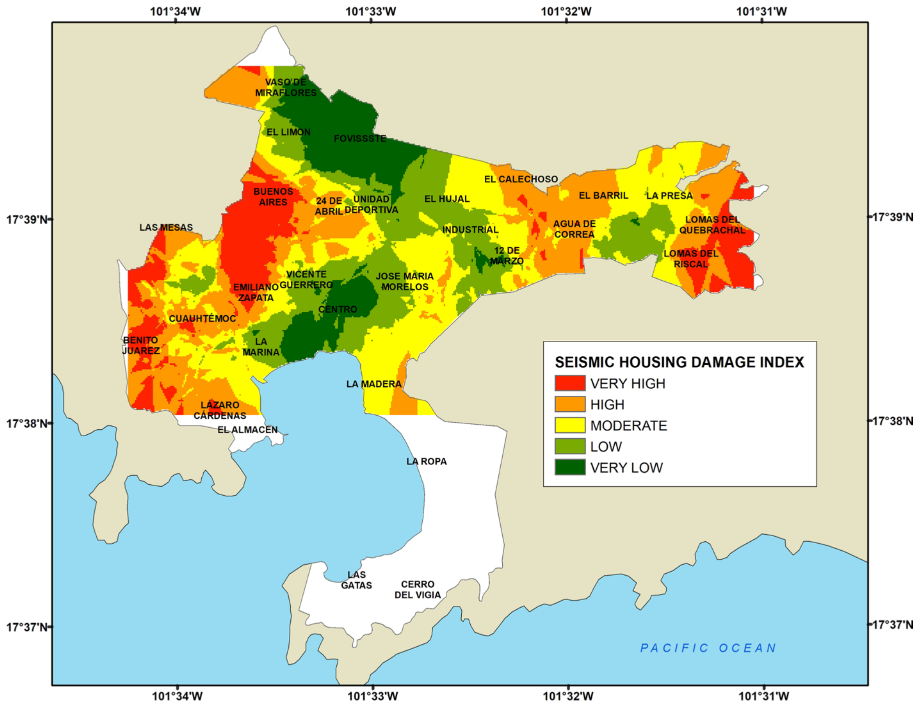

Fig. 5 Spatial distribution of the Seismic Index for Housing Typology (*SI*) in Zihuatanejo. For explanation of the white areas within the town see Fig. 4

2011). Another factor that conditions the high levels of social vulnerability in ZIH is the low number of houses with technology for accessing information. Cutter et al. (2003) stated that the main elements that influence social vulnerability are limitations for accessing education, information, knowledge, and technology.

The quality of housing construction is an important component in evaluating vulnerability. Low-income people, living in a marginal social situation, generally live in poorly constructed houses that are commonly vulnerable to strong earthquakes (Peek-Asa et al. 2003; Tierney 2006). In general, there are two types of soils in ZIH: a) Zone I is composed mainly of hard rock with low seismic amplification; b) Zone II is a mixture of hard and soft soils (GEOEXPLORA 2021) (Fig. 2). The more exposed areas to seismic structural damage are those located in soft soils. Normally, soft soils produce larger accelerations and seismic intensities than those observed at sites located on hard rock. Under these considerations, and based on the high levels of social and structural vulnerabilities in most of the eastern and western portions as well as the soil characteristics of ZIH, families living in houses located in Zone II are exposed probably to a higher level of seismic hazard than those in Zone I.

As would be expected, houses with a typology susceptible to be damaged by the impact of an earthquake in ZIH are in regions where the population is socially more vulnerable (Figs. 4 and 5). Poverty is the more important cause of high vulnerability to the impact of natural hazards (Hallegatte et al. 2020; Alexander 2012). In developing countries, the poorest people tend to build simple, traditional houses with their own labor and local low- or no-cost materials, usually adobe or other lightweight materials that increases their vulnerability and exposition to severe damage during a strong earthquake (Hausler 2010). However, earthquake-resistant houses can be built eventually if the right technology becomes locally available, widely known, and culturally accepted (Hausler 2010).

About 30% of the houses in ZIH have high or very high seismic structural vulnerability (Fig. 5). However, most districts in ZIH have moderate to very low level of structural vulnerability, mainly because most constructions and infrastructure are built over hard rock (Fig. 2).

Our findings indicate the importance of implementing preventive actions to reduce the social and structural vulnerabilities in ZIH. Admittedly, these types of solutions are both economic and technically challenging (Kenny 2009). Gao and Ji (2014) found that in Yunnan province, China, most residents did not consider earthquake-proof technologies to rebuild their homes because of their low income. Our results indicate that in general, the population of ZIH have similar socioeconomic conditions; therefore, engineering solutions may be difficult to implement in the short term. Thus, local programs to reduce the social and structural vulnerabilities in the medium and long term in ZIH are needed. There is a consensus among structural engineers that performance of constructions is enhanced by a regular geometry of the structure, avoiding soft stories, adequate foundations, and lightweight roofing, amid other factors (Laghi 2017; Murty 2005). Also, wood could be one of the more important and dependable construction materials because it is renewable and has high resistance to earthquakes (Salman and Hussain 2010).

This study identifies those areas that are priority for seismic risk management measures and provides information of where to focus actions for disaster response and prevention plans in ZIH. We hope that the results of this assessment may provide the framework for the implementation of seismic prevention measures at the local level.

5 Conclusions

This study determined the susceptibility of ZIH to the impact of large and major earthquakes. It shows that approximately 50% of the population and 30% of the houses have a high or very high social and seismic structural vulnerability, respectively. Our findings indicate that high social vulnerability is prevalent in female-headed households and families lacking technology for accessing education and information (telephone, internet, etc.). The houses with the typology more susceptible to earthquake damage are located to the west and east of ZIH. Not surprisingly, in these areas the population is also socially vulnerable.

It is important for local authorities to develop strategies to diminish the structural and social vulnerabilities in regions with high and very high vulnerability identified here. Based on our results, mitigation actions should be prioritized in the Lázaro Cárdenas, Benito Juárez, Cuauhtémoc, Emiliano Zapata, Las Mesas, Buenos Aires, Lomas del Quebrachal, and Lomas del Riscal districts that could suffer higher levels of damage by a strong earthquake than other zones in ZIH. Also, promotion in the mid and long term of low-cost earthquake-resistant houses is the essential tool to reduce the impact of earthquake-related disasters. Thus, a multifaceted seismic risk management approach embracing structural and non-structural measures including land-use regulations and early warning systems are recommended in ZIH. This approach must be based on a holistic and societal analysis to determine those elements that condition the social construction of risk. The development of public policies for risk prevention and mitigation is also required to reduce the impact of future earthquakes in the ZIH community.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethical approval The authors declare that the autonomy of individuals in this research was strictly observed and respected. All personal data provided by participants during the house-to-house surveys were protected and remain confidential and anonymous. In the resulting data, interviewees cannot be identified directly or indirectly. Before the interviews, participants were provided with ample information regarding the purpose of the research. This allowed participants to make an informed and conscientious decision to take part in the research or not. Participants were not subjected to any form of coercion to be part of this research. The interviewees were aware that they were free to withdraw from the research at any time without giving a reason and without prejudice. The research was conducted with integrity and transparency.

References

Alexander D (2012) Model of social vulnerability to disasters. RCCS Annual Rev. 4:22–40

Anderson JG, Singh SK, Espindola JM, Yamamoto J (1989) Seismic strain release in the Mexican subduction thrust. Phys Earth Planet Int 58:307–322. https://doi.org/10.1016/0031-9201(89)90102-7

Birkmann J (ed) (2006) Measuring vulnerability to natural hazards: towards disaster resilient societies. United Nations University Press, Tokyo

Cocco M, Pacheco J, Singh SK, Courboulex F (1997) The Zihuatanejo, Mexico, earthquake of 1994: source characteristics and tectonic implications (1997). Geophys J Int 131:135–145. https://doi.org/10.1111/j.1365-246X.1997.tb00600.x

Cutter SL, Boruff BJ, Shirley WL (2003) Social vulnerability to environmental hazards. Soc Sci Q 84:242–261. https://doi.org/10.1111/1540-6237.8402002

Drakes O, Tate E, Rainey J, Brody S (2021) Social vulnerability and short-term disaster assistance in the United States. Int J Dis Risk Red 8:1–22. https://doi.org/10.2202/1547-7355.1792

Flanagan BE, Gregory EW, Hallisey EJ, Heitgerd JL, Lewis B (2011) A social vulnerability index for disaster management. J Home Sec Emer Manag 8:1–22. https://doi.org/10.2202/1547-7355.1792

Gao X, Ji J (2014) Analysis of the seismic vulnerability and the structural characteristics of houses in Chinese rural areas. Nat Hazards 70:1099–1114. https://doi.org/10.1007/s11069-013-0860-2

GEOEXPLORA (2021) Zihuatanejo microzonation by using the spectral ratios (H/V) and multichannel analysis of surface waves (MASW), Monitoring Geophysical Survey Report to the Science and Technology Research Partnership for Sustainable Development (SATREPS) project

Hallegattte S, Vogt-Schilb A, Rozenberg J, Bangalore M, Beaudet C (2020) From poverty to disaster and back: a review of the literature. Ec Dis Clim Chan 4:223–247. https://doi.org/10.1007/s41885-020-00060-5

Hausler E (2010) Building earthquake-resistant houses in haiti, the homeowner-driven model. Innov Tech Gov Glob 5:91–115

Ignacio JAF, Grace TC, Nardi F, Sabine H (2016) Assessing the effectiveness of a social vulnerability index in predicting heterogeneity in the impacts of natural hazards: Case study of the Tropical Storm Washi flood in the Philippines Special. Vienna Yearbook of Population Res. 13:91–129

Iida K, Cox DC, Pararas-Carayannis G (1967) Preliminary catalog of tsunamis occurring in the Pacific Ocean, Hawaii Institute of Geophysics, Data Report No. 5 HIG-67–10

Jenks GF (1967) The Data Model Concept in Statistical Mapping. International Yearbook of Cartography 7:186–190

Kenny C (2009) Why do people die in earthquakes? The costs, benefits, and institutions of disaster risk reduction in developing countries. World Bank Policy Research Working Paper No. 4823. https://doi.org/10.1596/1813-9450-4823

Kostoglodov V, Ponce L (1994) Relationship between subduction and seismicity in the Mexican part of the Middle America trench. J Geophys Res 99:729–742

Laghi V, Palermo M, Trombetti T, Schildkamp M (2017) Seismic-proof buildings in developing countries. Front Built Environ 3:49. https://doi.org/10.3389/fbuil.2017.00049

Murty CVR (2005) Earthquake Tips: Learning Earthquake Design and Construction. Kanpur, India: National Information Center of Earthquake Engineering, Indian Institute of Technology Kanpur

Nishenko SP, Singh SK (1987) Conditional probabilities for recurrence of large and great interplate earthquakes along the Mexican subduction zone. Bull Seism Soc Am 77:2095–2114. https://doi.org/10.1785/BSSA0770062095

Novelo-Casanova DA, Rodriguez-Vangort F (2016) Flood risk assessment. Case study: Motozintla de Mendoza. Chiapas Mexico Geomat Nat Hazards Risk 7:1538–1556. https://doi.org/10.1080/19475705.2015.1089327

Novelo-Casanova DA, Ponce-Pacheco A, Hernández-Hernández A, Juárez-Sanchez A, López-Pérez MI, Hernández-Bello MG, De La Vega-Flores O (2019) Seismic and flood structural risk in Motozintla, Chiapas, Mexico. Nat Hazards 95:721–737

Novelo-Casanova DA, Suárez G, Cabral-Cano E, Fernández-Torres EA, Fuentes-Mariles OA, Havazli E, Jaimes MA, López-Espinoza ED, Martin-Del Pozzo AL, Morales-Barrera WV, Morales-Rodríguez HL, Nieto-Torres A, Rodríguez-Elizarrarás SR, Solano-Rojas D, Velasco-Herrera VM (2022) The risk atlas of Mexico City, Mexico: a tool for decision-making and disaster prevention. Nat Hazards 111:411–437. https://doi.org/10.1007/s11069-021-05059-z

Peek-Asa C, Ramirez M, Seligson H, Shoaf K (2003) Seismic, structural, and individual factors associated with earthquake related injury. Inj Prev 9:62–66. https://doi.org/10.1136/ip.9.1.62

Plata-Martinez R, Ide S, Shinohara M, Garcia ES, Mizuno N, Dominguez LA, Taira T, Yamashita Y, Toh A, Yamada T, Real J, Husker A, Cruz-Atienza VM, Ito Y (2021) Shallow slow earthquakes to decipher future catastrophic earthquakes in the Guerrero seismic gap. Nature Com 12:3976. https://doi.org/10.1038/s41467-021-24210-9

Rashed T, Weeks J (2003) Assessing vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas. Int J Geo-Inf 17:547–576. https://doi.org/10.1080/1365881031000114071

Reyes-Salinas C, Flores-Corona L, Pacheco-Martínez MA, López-Bátiz O, Valerio-Zárate LA, Zepeda-Ramos O (2004) Evaluación Simplificada de la Vulnerabilidad de la Vivienda Unifamiliar ante Sismo y Viento [Simplified Evaluation of the Vulnerability of Single-Family Housing in the case of Earthquakes and Wind, in Spanish]. In: Guía Básica para la Elaboración de Atlas Estatales y Municipales de Peligro y Riesgos, CENAPRED, pp 311–338

Salman F, Hussain M. (2010) Earthquake Resistant Wooden House, Ph.D. Department of Building Technology, School of Engineering, Linnaeus University, https://www.diva-portal.org/smash/get/diva2:322657/fulltext01.pdf, (accessed 13 April 2022)

Sanchez AJ, Farreras SF (1993) Catalog of tsunamis along the western coast of Mexico. World data Center for Solid Earth Geophysics, Publication SE-50, National Geophysical Data Center, NOAA, Boulder, Colorado, U.S.A., 79p

Singh SK, Astiz L, Havskov J (1981) Seismic gaps and recurrence periods of large earthquakes along the Mexican subduction zone: a reexamination. Bull Seism Soc Am 71:827–843. https://doi.org/10.1785/BSSA0710030827

Singh SK, Pacheco JF, Shapiro N (1998) The earthquake of 16 November 1925 (M_s=7.0) and the reported tsunami in Zihuatanejo. Geof Int 37:49–52

Suárez G, Albini P (2009) Evidence for great tsunamigenic earthquakes (M 8.6) along the Mexican subduction zone. Bull Seism Soc Am 99(2A):892–896. https://doi.org/10.1785/0120080201

Tierney K (2006) Social inequality: humans and disasters. In: Daniels RJ, Keitl DF, Kunreuther H (eds) On Risk and Disaster: Lessons from hurricane Katrina. University of Pennsylvania Press, Philadelphia

Yates DS, Moore DS, Starnes DS (2008) The Practice of Statistics, 3rd edn. Freeman, New York