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Seismic hazard in the metropolitan area of Tuxtla Gutiérrez: two case studies

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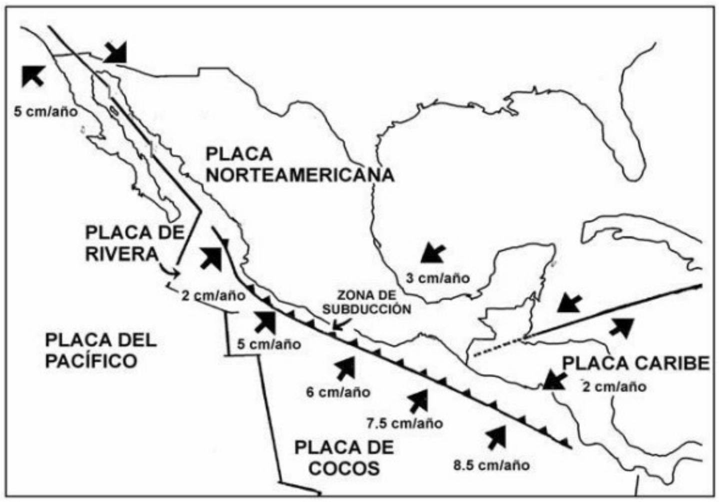
— Abstract—

In the metropolitan area of Tuxtla Gutiérrez, made up of the municipalities of Tuxtla Gutiérrez, Chiapa de Corzo, Berriozábal, San Fernando, and Suchiapa, the interaction of human activity with natural features has given rise to dangerous scenarios in which the region presents different levels of vulnerability to seismic events. The consequences of the earthquakes that occurred in this southeastern region of the Mexican Republic have claimed lives, generating significant damage that has transcended the groups with the greatest degree of marginalization of the population. This research addresses historical damage and soil thicknesses as indicators of the site effect for analyzing the seismic hazard of two municipalities: Tuxtla Gutiérrez and Chiapa de Corzo. A multiparameter methodology (Moreno Ceballo et al., 2019, Moreno Ceballo et al., 2020) based on Geographic Information Systems was used, which included a documentary review and a field record of historical damage due to earthquakes in the two localities, the seismic microzonings of these cities that have fundamental periods of ground vibration that vary between 0.14 s and 0.39 s for Chiapa de Corzo (Salgado et al., 2004) and between 0.08 s and 1.33 s for Tuxtla Gutiérrez (González-Herrera et al., 2013, Narcía López et al., 2006). With the model used by Newmark and Rosenbluth (1976), the variation of sediment thicknesses that leads to the site effect in the area was obtained, considering an average shear wave velocity of 150 m/s. Finally, sediment thickness maps were prepared for both urban areas, ranging from 7.12 m to 14.62 m for Chiapa de Corzo and between 3 m and 46.78 m for Tuxtla Gutiérrez, and a spatial correlation was made with the historical damage caused by earthquakes in both localities.

Keywords:

Seismic amplification; map, seismic microzonation; seismic vulnerability.

In Mexico, much of the national territory presents a significant seismic risk, generated mainly by the earthquakes occurring on the Pacific Ocean coast, at the conjunction of the Cocos and North American tectonic plates. Chiapas is a region considerably prone to seismic activity, due to a unique feature in the rest of the Mexican Republic, in which three tectonic plates converge: the Cocos Plate, the North American Plate, and the Caribbean Plate (Figure 1).



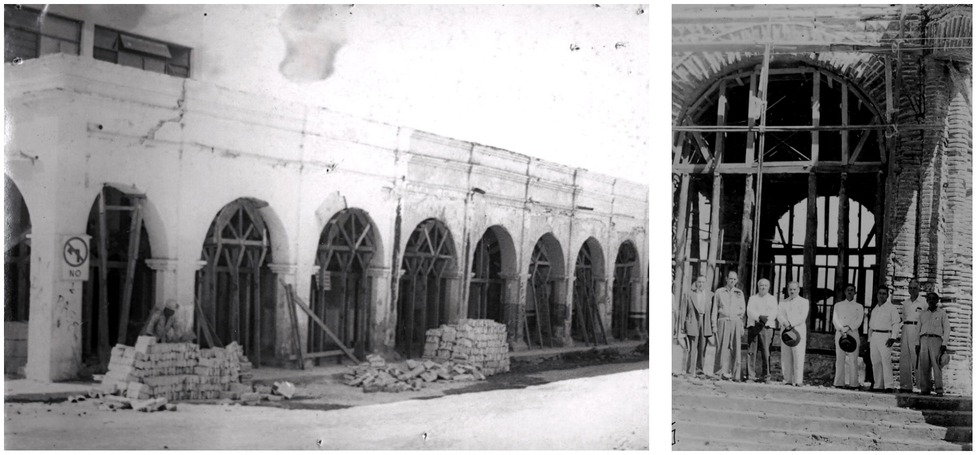
Note. (CENAPRED, 2006).

Figure 1. Tectonic plates that interact in the state of Chiapas with their respective movement direction

Chiapas is divided into four tectonic provinces: the province of the Inverse Fallas, the province of the Lateral Fallas, the Batolito de Chiapas, and the Motagua-Polochic Fallas (Guzmán & Meneses, 2000) and five seismogenic sources have also been identified (González-Herrera, 2014) that have originated the earthquakes that occurred in the region, the first being the subduction process of the Cocos plate under the North American Plate (Suárez & Singh, 1986; Pardo & Suárez, 1995). The second source is associated with the internal deformation of the subducted plate, which produces earthquakes ranging from 80 to 300 km deep, of the intra-plate type, such as the one that occurred on September 7, 2017, of 8.2 Mw. The third source corresponds to surface fault systems that have caused a cortical deformation, which originates tremors of moderate magnitude and depth (González-Herrera et al., 2015).

These earthquakes cause local damage, such as those that occurred in Chiapa de Corzo between July and October 1975 (Figure 2a and 2b) (Nadayapa, 2011). The presence of active volcanoes in the state (the Tacaná and the Chichonal or Chichón) and the left lateral faulting between the

North American Plate and the Caribbean Plate (González-Herrera, 2015) correspond to the fourth and fifth source, respectively.



a) b)

Note. (Nandayapa, 2011).

Figura 2. Damage to the portals and the fall of one of the ends of the arches of Chiapa de Corzo's colonial fountain

STUDY AREA

Metropolitan Areas (MA) are defined as a group of municipalities related to each other by a high degree of physical or functional integration on an inter-municipal or interstate basis. Another requirement to be classified as an MA is that the total population of the municipalities that comprise it is greater than 200 thousand inhabitants and that the urban locality or conurbation that gives rise to it has more than 100 thousand inhabitants (SEDATU, 2020).

The dynamics of development and economic growth experienced by some cities, such as Tuxtla Gutiérrez, have led them to exceed their municipal boundaries (INEGI, 2014), which has caused them to update their composition. In 2023, the document "Metrópolis de México 2020" was published, the result of a collaborative work between the National Population Council (CONAPO), the National Institute of Statistics and Geography (INEGI), and the Ministry of Agrarian, Territorial, and Urban Development (SEDATU), which defines 48 MAs in Mexico, comprised of 345 municipalities in which 67.6 million people reside.

Therefore, the Tuxtla Gutiérrez MA (Figure 3) is made up of this municipality (capital of the state of Chiapas), as well as Berriozábal, Chiapa de Corzo, Suchiapa, and San Fernando, as shown in Table 1.

Table 1
Municipalities that make up the Metropolitan Area of Tuxtla Gutiérrez

Municipalities	Surface area (Km²)	Altitude	Number of Inhabitants
Tuxtla Gutiérrez	334.61	527	604,147
Chiapa de Corzo	829.98	509	112,075
Berriozábal	351.70	904	64,632
Suchiapa	283.66	460	25,627
San Fernando	359.26	912	41,793

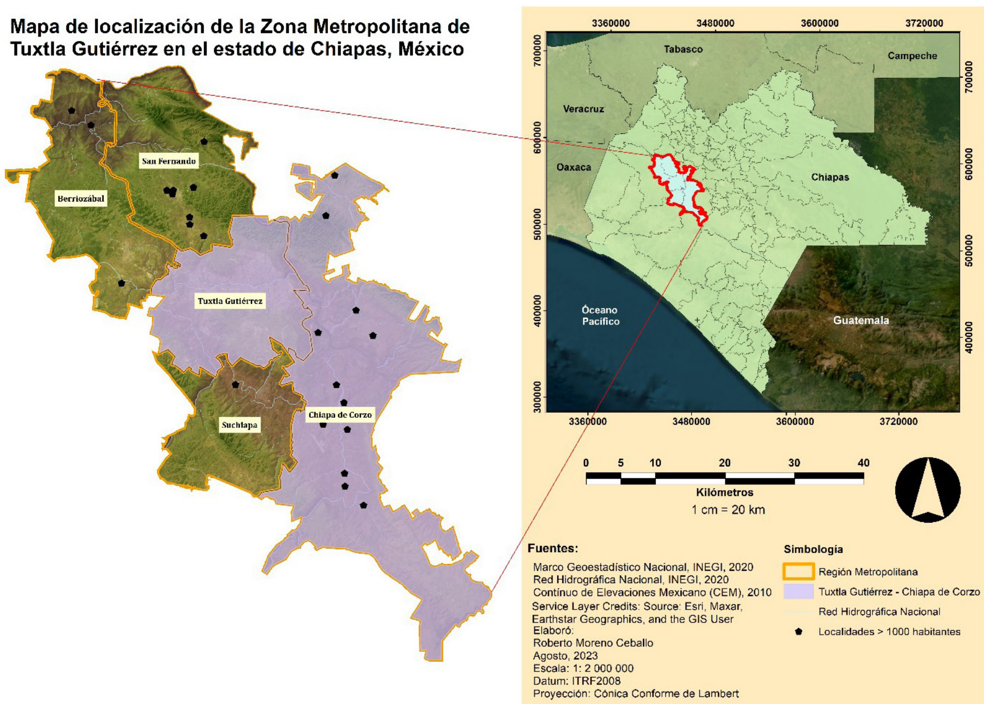


Figure 3. Location map of the Metropolitan Region of the state of Chiapas, Mexico

The MA of Tuxtla Gutiérrez has experienced significant growth in the period between 2010 and 2020, at the population level, it increased by more than 100 thousand inhabitants, which represents an increase of approximately 14 percent (Figure 4).

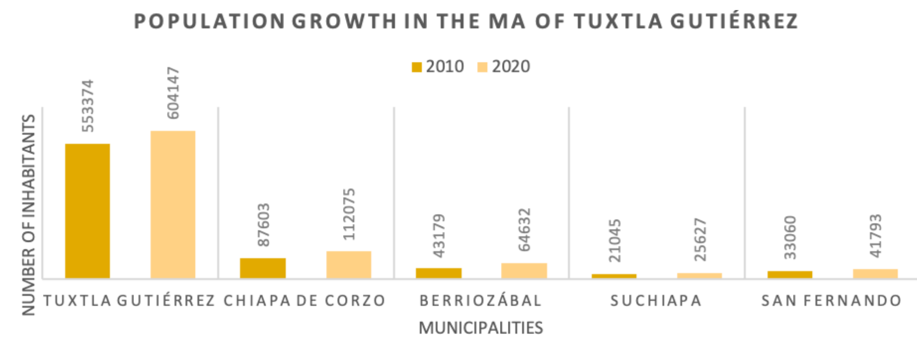


Figure 4. Population growth in the Metropolitan Area of Tuxtla Gutiérrez, according to the INEGI population censuses of 2010 and 2020, respectively

General characteristics of the study area

In the northern part of the region, the high mountain range with sloping slopes predominates, followed by a complex steep high mountain range; to the south of the region, the plateau with glens predominates, followed by the high mountain range with sloping slopes and in a smaller proportion of areas with typical canyons. In the eastern part of the region there is the valley of slopes stretched with homerio and high mountain range of steep slope; in the western part of the region the typical homerio predominates, in the center of the region there is the typical plateau and alluvial plain with homerio (Mullerried, 1957), in this area there is the Cañon del Sumidero, a large geoform product of a system of faults and geological fractures, in addition to the erosive action of the Grijalva River; the relief forms with little slope with hills, plateaus, and valleys predominate in the center, which represents approximately 60% of the territory.

The relief's height ranges from less than 30 m to 2,600 m above sea level (INEGI, 2004). In the study area, 8 soil units are generally presented, within which there is a greater percentage distribution of Litosol, Regosol, and Rendzina:

Table 2
Metropolitan Area Soil Units

Soil units	Percentage distribution
Litosol	38.04
Regosol	20.90
Rendzina	14.38
Vertisol	10.51
Luvisol	4.91
Acrisol	4.55
Feozem	3.54
Fluvisol	1.67
Body of water	0.93
Urban Area	0.58

Note. (INEGI. Topographic map scale 1:250,000 Series III. INEGI. Municipal Geostatistical Framework 2005).

In terms of geology, the surface of the MA has seven types of rock and is composed of tertiary soils, with three types predominating: limestone (34.46%), limonite-sandstone (29.01%), and shale-sandstone (16.55%). Also from Cretaceous soils: siltstone (7.35%) and alluvial (07.22%). Other varied soil compositions make up the remaining 05.40% of the region's land area (Secretary of the Treasury, 2017).

Seismicity in the region

The earthquakes that have occurred in the region have had a strong impact on the southeastern region of Mexico, with a considerable impact on the most marginalized groups of the population. According to the population and housing census conducted by INEGI in 2010, over 70% of the region's population has a medium to high level of marginalization. The analysis of the seismic hazard in a given region involves the management of a large amount of information. This paper presents the results obtained for two case studies: Tuxtla Gutiérrez and Chiapa de Corzo. Both sites were selected for the existence of buildings with high heritage value, for having a housing stock with a certain degree of deterioration, and for the presence of areas with a high degree of marginalization.

The effect of earthquakes in the aforementioned cities can be appreciated at different scales, at the state level because they have suffered major earthquakes that affected buildings that are part of the cultural heritage of humanity, as in the case of Chiapa de Corzo (earthquakes of October 1975), or the earthquake of October 1995 in Tuxtla Gutiérrez, and at the local level because of the characteristics of the soil and the levels of seismic amplification. The occurrence of large magnitude events (Figure 5), such as the one that occurred on September 07, 2017 (8.2 Mw), reiterates the need to conduct hazard studies in areas of extensive cultural richness.

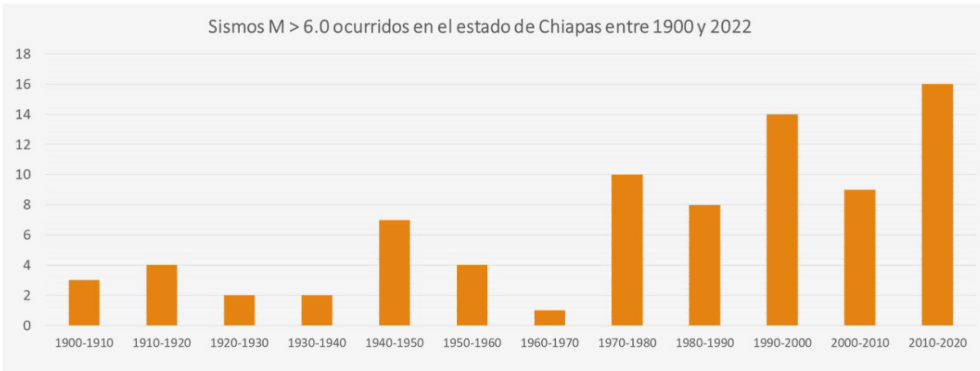


Figure 5. Earthquakes occurring in the state of Chiapas between 1900 and 2022 with magnitude M>6

METHODOLOGY

For this research, a multi-parameter methodology was used (Moreno Ceballo et al., 2019, Moreno Ceballo et al., 2020) based on Geographic Information Systems, which contemplated the geological, edaphological characteristics, and the areas susceptible to flooding or floodplains were also determined. A database of historical earthquake damage in the region, much of it collected in the field between 2017 and 2020, was also used:

Documentary review and field data collection

Documentary review of the seismic events recorded in the study area, based on surveys applied to the population and semi-structured interviews with chroniclers and historians. This allowed a compilation of the damages presented with the occurrence of seismic events in the region, highlighting those that occurred on October 6, 1975 (for the case of Chiapa de Corzo) and the earthquake of September 7, 2017, of 8.2 Mw.

The historical damage databases were built by strengthening the documentary research with field work, where the use of the properties from 1975 to the present was also considered (Moreno-Ceballo et al., 2020). A GPS/GNSS navigator was used to geographically reference the buildings damaged by the seismic events considered for this work.

Flooded areas

Areas adjacent to riverbeds are very attractive for urban development, the use of such areas, without considering the natural limits necessary to evacuate floodwaters, has contributed to amplify the negative effect of floods, which in some cases leave tragic consequences (Arbeláez et al., 2002). Therefore, flood areas were identified due to the presence of major rivers that have historically affected urban areas in the study area, such as the floods caused by Hurricane Arthur in 2008 (Hernández, 2009) and Hurricane Matthew in 2010 (López, 2010) in Chiapa de Corzo.

Soil movement amplification is one of the main causes of significant damage in areas with poorly compacted sedimentary deposits. According to Schmudde (1968), the floodplain, a geomorphological form generally composed of unconsolidated material transported by rivers, favors this phenomenon. These soils increase seismic amplification, intensifying the effects of an earthquake. In general, the damage caused is related to variations in near-surface geologic materials and, in particular, these amplifications of ground motion are associated with recent and poorly consolidated sedimentary deposits (Tinsley & Fumal, 1985).

Degree of damage and determination of vulnerability

For the assignment of the degree of damage and determination of seismic vulnerability, the European Macroseismic Scale (EME) was used, which considers a description and graphic scheme, and defines qualitatively each of the five degrees of damage; where the degree of damage varies from degree 1, which corresponds to negligible damage, to degree 5, which is associated with the total collapse of the building (Grunthal, 1998), (Arellano et al., 2003), (Silva, 2006). The quality of the building was also analyzed taking into account the materials used and the areas of greatest seismic amplification were determined based on measurements of the fundamental periods of soil vibration and their subsequent comparison with the thickness of sediments and the use of the following variables: Soil science, geology, historical damage, seismic amplification.

Map production

Finally, maps containing information on historical seismic damage and sediment thickness were prepared for urban patches. In 1976, Newmark and Rosenbluth coined the expression relating sediment thickness to its fundamental period of vibration and shear-wave propagation velocity:

$$T = 4\sum_{i}^{n} \frac{hi}{\beta i} \qquad (1)$$

Where T represents the natural period of the terrain, *h* is the thickness of the *ith* stratum, and β is the speed of propagation of shear waves. The number of sedimentary strata is represented by *n*. From this model, we can obtain the definitive equation with which the ArcMap software was fed in order to obtain the values that were subsequently interpolated:

$$h_i = \frac{(Tx\beta i)}{4}) \qquad (2)$$

To estimate the sediment thicknesses under both urban patches, the model described above was used, in addition to the calculation of the natural periods of vibration of the soils. For this, an average β velocity of 150 m/s was used (Narcía et al., 2006). The periods used for Chiapa de Corzo correspond to those found by Salgado et al. (2004), while in the case of Tuxtla Gutiérrez, 285 measurements were used throughout the urban area (Figure 6).

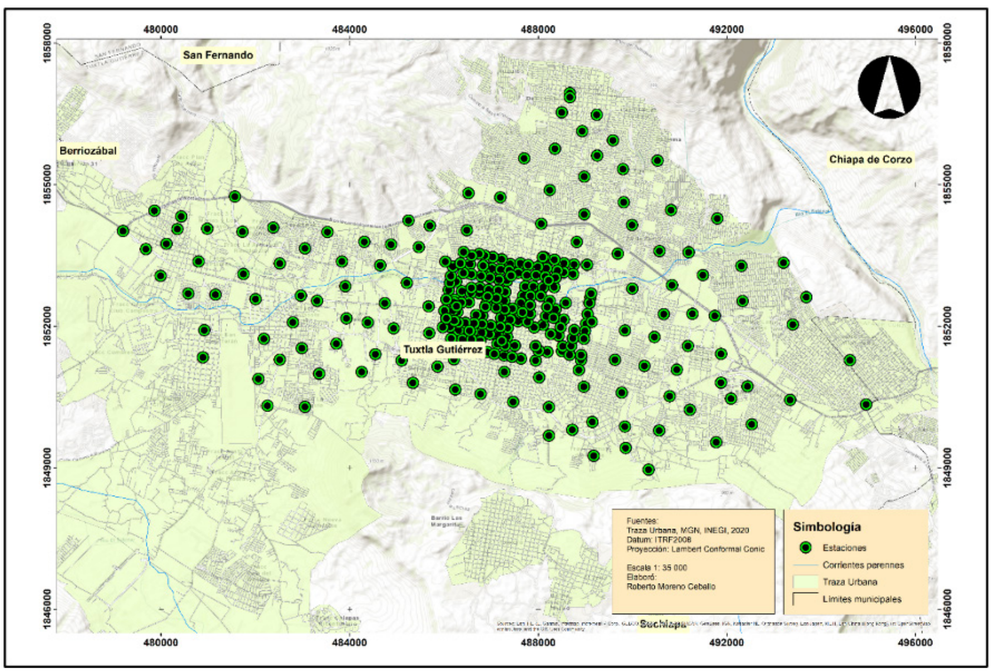


Figure 6. Location of the stations to measure the fundamental periods of environmental vibration in the municipal capital of Tuxtla Gutiérrez

CHIAPA DE CORZO

Chiapa de Corzo is located on federal highway 190, just 12 km from Tuxtla Gutiérrez, the capital of the state of Chiapas. The capital of the municipality is located on the limits of the Central Depression and the Central Highlands, its geographical coordinates are 16º 42"N and 93º 00" W (497920.00 m E and 1849152.00 m N, Zone 15 N), its altitude is 406 masl and has a territorial extension of 869.21 km² (INAFED, 2018). It borders to the north with the municipalities of Osumacinta, Soyaló, and Ixtapa; to the east with the municipalities of Ixtapa, Zinacantán, Acala, and Venustiano Carranza; to the south with the municipalities of Venustiano Carranza and Villa Corzo; to the west with the municipalities of Villa Corzo, Villaflores, Suchiapa, Tuxtla Gutiérrez, and Osumacinta (INEGI, 2008).

The municipality of Chiapa de Corzo has geological characteristics, where limestone predominates by 40.84%, Lutite – Sandstone (27.06%), Siltstone – Sandstone (13.22%), Limestone – Lutite (10.56%), Conglomerate (7.44%), Basic Intrusive Igneous (0.74%) and Sandstone – Conglomerate (0.12%) (INEGI, 2008).

As for the edaphological characteristics, the eastern portion of the population is made up of a calcareous Regosol, and in this area, there are some low ridges. The west side and a small portion to the south are in a Vertisol; likewise, another area to the southwest of the town is constituted by an eutric Fluvisol. To the south and southwest is the body of water that constitutes the Rio Grande de Chiapa or Rio Grijalva. Most of the historic center of Chiapa de Corzo is substantially flat (Salgado et al., 2004).

The map in Figure 7 illustrates the distribution of earthquake damage in the municipal capital of Chiapa de Corzo, where a concentration can be seen in the central area and the areas near the Grijalva River. Several important buildings have been repeatedly affected, such as the Temple of Calvary, the Church of Santo Domingo, the Church of San Jacinto, and some homes that survived both seismic events. The greatest number of affectations corresponds to traditional adobe houses, approximately 30% of the buildings surveyed during field work; it is important to specify that adobe generally presents poor structural behavior during the occurrence of natural phenomena such as earthquakes.

Amplification of local terrain may be due to the nature, composition, and morphology of the surface layers of soil. This local phenomenon of terrain behavior is known as the "local effect", "local response", or "site effect" (Rodríguez, 2005). The damage presented in the buildings is caused, to a large extent, by the amplification of soil movement, which is greater in areas constituted by deposits of soft and poorly compacted sediments, such as areas near the river bank.

Geomorphologically, the flood plain is a landform composed primarily of unconsolidated deposited material, derived from sediments transported by the river in question (Schmudde, 1968). The presence of this type of soil favors seismic amplification, causing a greater site effect in the event of an earthquake. For this reason, after a thorough documentary review, as well as the incorporation of Civil Protection reports, a map of the Maximum Extraordinary Water Level (NAME) for the municipal capital of Chiapa de Corzo was drawn up (Figure 8).

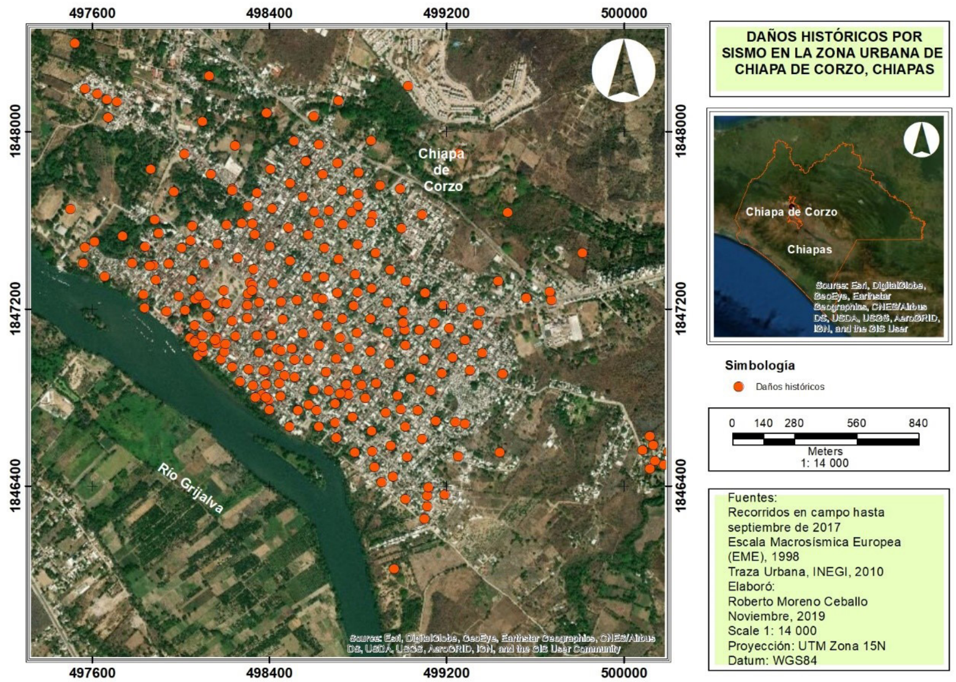
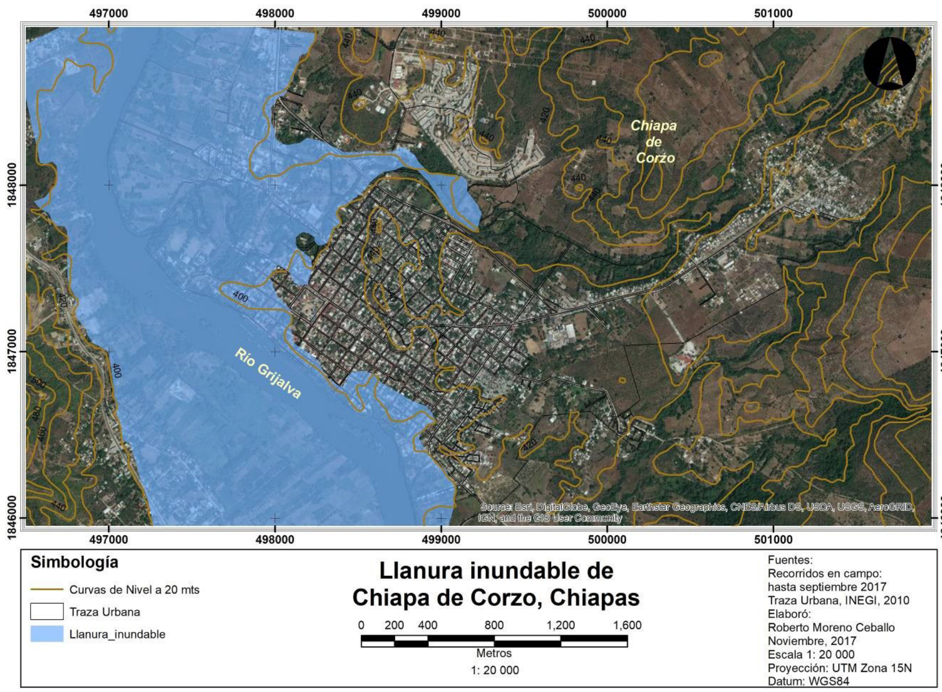


Figure 7. Location of historical damage in Chiapa de Corzo, Chiapas, in two seismic events

Overall, earthquake shaking damage is commonly related to variations in near-surface geologic materials and, in particular, these large amplifications of ground motion are associated with recent and poorly consolidated sedimentary deposits (Tinsley & Fumal, 1985).

Town development plans should consider the local seismic response of the subsoil, in order to define specific seismic-resistant structural design parameters, according to the seismic history of the region (IPCMIRD, 2010). This research mainly addresses the physical part within the analysis of seismic risk, studying the current state of the buildings and the construction process of vulnerability, mainly due to human intervention that, in the absence of technical advice, resort to self-construction processes or the use of materials that do not comply with the corresponding regulations.



Note. (Moreno-Ceballo et al., 2019).

Figure 8. Floodplain of the municipal capital of Chiapa de Corzo

In the region, the use of reinforced brick predominates, followed by adobe, which has traditionally been the most used material for housing walls in the area, due to its economy, ease of manufacture, construction, and thermal benefits (Moreno-Ceballo et al., 2019). With the occurrence of earthquakes that have locally affected Chiapa de Corzo (Table 3) and the state of Chiapas in general, it is imminent that local soil conditions are determinant in the structural response.

Table 3
Earthquakes that have affected Chiapa de Corzo

Date	Latitude	Length	Magnitude
05/06/1897	16.30	-95.40	7.4
19/04/1902	14.90	-91.50	7.5
23/09/1902	16.60	-92.60	7.7
14/01/1903	15.00	-93.00	7.6
09/12/1912	15.50	-93.00	7.0
30/03/1914	17.00	-92.00	7.2
10/12/1925	15.50	-92.50	7.0
28/06/1944	15.00	-92.50	7.1
26/09/1955	15.50	-92.50	6.9
09/11/1956	17.45	-94.08	6.3
29/04/1970	14.52	-92.60	7.3
05/10/1975	16.74	-92.92	4.8
10/09/1993	14.20	-92.80	7.2
14/03/1994	15.98	-92.43	6.8
21/10/1995	16.81	-93.47	7.1
18/11/2001	15.45	-93.60	6.3
16/01/2002	15.58	-93.60	6.3
07/09/2017	15.76	-93.70	8.2

Note. (Salgado et al., 2004; SSN, 2017).

This must be accompanied by the analysis of seismic amplification at the local level. In this research, we consider sediment thickness as an additional variable to understand the spatial behavior of the damage presented. For this purpose, the data obtained by Salgado and collaborators (2004) were used, which present fundamental vibration periods ranging from 0.14s to 0.39s (Figure 9).

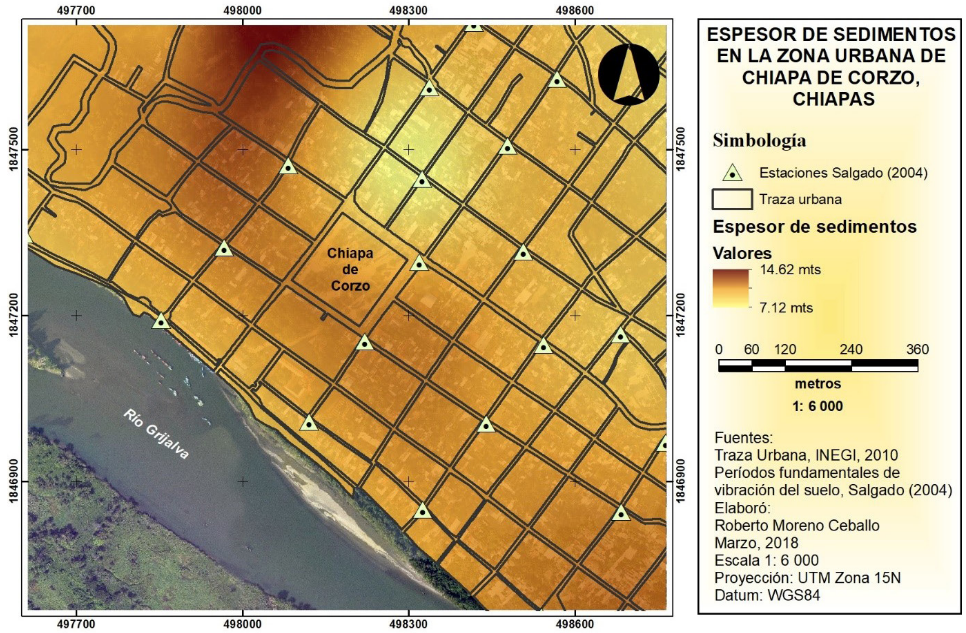


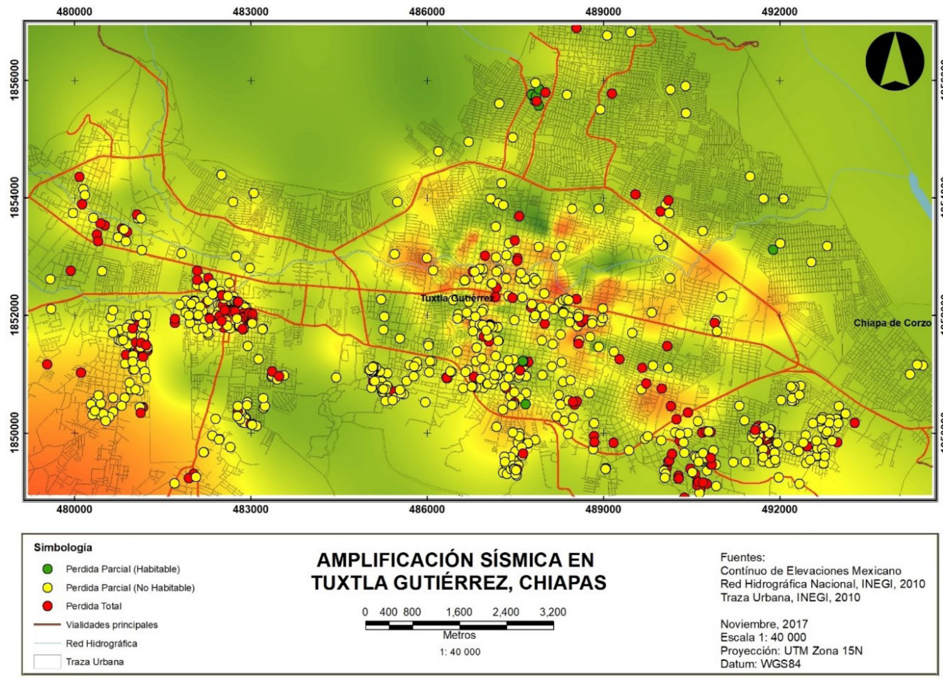
Figure 9. Sediment thickness map for the municipal capital of Chiapa de Corzo, Chiapas

TUXTLA GUTIÉRREZ

Located in the Central Depression of the state of Chiapas, it has mountainous relief to the north and south. Its territorial extension is 412.40 km², which represents 3.26% of the Central region and 0.55% of the state's surface. This city is bordered to the north by the municipalities of San Fernando and Usumacinta, to the east by Chiapa de Corzo, to the south by Suchiapa, and the west by Ocozocuautla and Berriozábal (CEIEG, 2010).

The municipal territory is made up of high mountain ranges with steep slopes, plains with alluvial deposits, and plateaus due to erosion; in the northern part, there is a set of mountain ranges whose altitude does not exceed 1,200 masl. The northern slope is stable and is made up of Upper Cretaceous limestone (Ocozocoautla-La Angostura formation), and corresponds to the flanks of the Mesa de la Animas. On the other hand, the southern slope is unstable by nature (Paz, 2012), since it corresponds to recent colluvium-type deposits, generated from materials detached from the edges of the Copoya karst table (Paz et al., 2011), which is composed of limestones and sandstones of the middle Eocene (San Juan formation) (Ferrusquia et al., 2000, cited in Paz-Tenorio et al., 2017).

The signal measured on the ground during the occurrence of a seismic event has different durations (Atakan et al., 1997; Lermo & Chávez-García, 1993), especially in those with an unstable composition. This is due to the change that seismic waves undergo as they pass through the different soil strata.



Note. (González et al., 2020).

Figure 10. Seismic amplification in Tuxtla Gutiérrez, Chiapas

Figure 10 presents a map of seismic amplification in Tuxtla Gutiérrez (González-Herrera et al., 2012), where the damages of the earthquake of September 7, 2017 (8.2 Mw) can also be observed, highlighting a significant number of total and partial losses caused by this phenomenon. When the materials and construction systems used are homogeneous, so is the vulnerability of the constructions; this means that the results are conditioned by the effects of the site (Moreno et al., 2019).

In addition, it is located within the Sabinal River basin and is immersed within the Hydrological Region Number 30, Grijalva-Usumacinta. It has a length of 407 km, of which 148.96 km are located in the municipality of Tuxtla Gutiérrez, which represents approximately 36%. It is born on the hill "El Chupadero", 5 km northwest of the municipality of Berriozábal (to the west) and runs 46.4 km to flow into the Grijalva River (east of the city of Tuxtla Gutiérrez) in the municipality of Chiapas de Corzo (García Benítez, et al., 2022). Figure 11 shows a map of the floodable areas in Tuxtla Gutiérrez, prepared from Municipal Civil Protection reports in the period between 2004 and 2016.

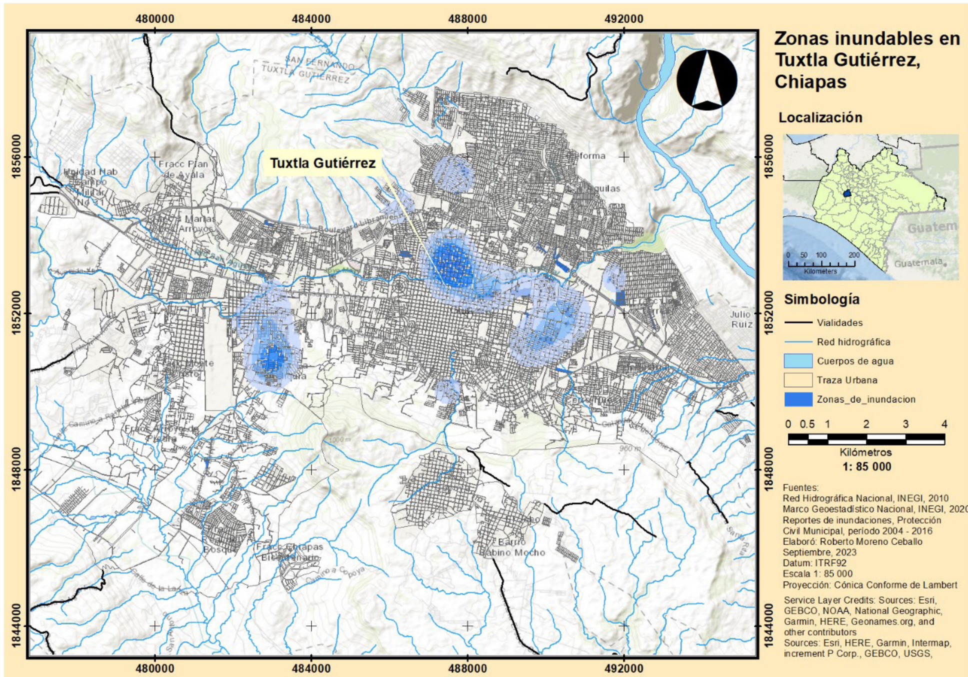


Figure 11. Tuxtla Gutiérrez's floodplain areas, map prepared from municipal Civil Protection flood reports in the period between 2004 and 2016

Finally, using the model proposed by Newmark and Rosenbluth in 1976, the sediment thicknesses (Figure 12) were obtained for Tuxtla Gutiérrez. The records were taken at 285 stations located at different points of the urban area (Figure 6); the periods obtained range from 0.08s to 1.33min. In addition, the spatial distribution of the damage caused by the earthquake of September 7, 2017, can be observed.

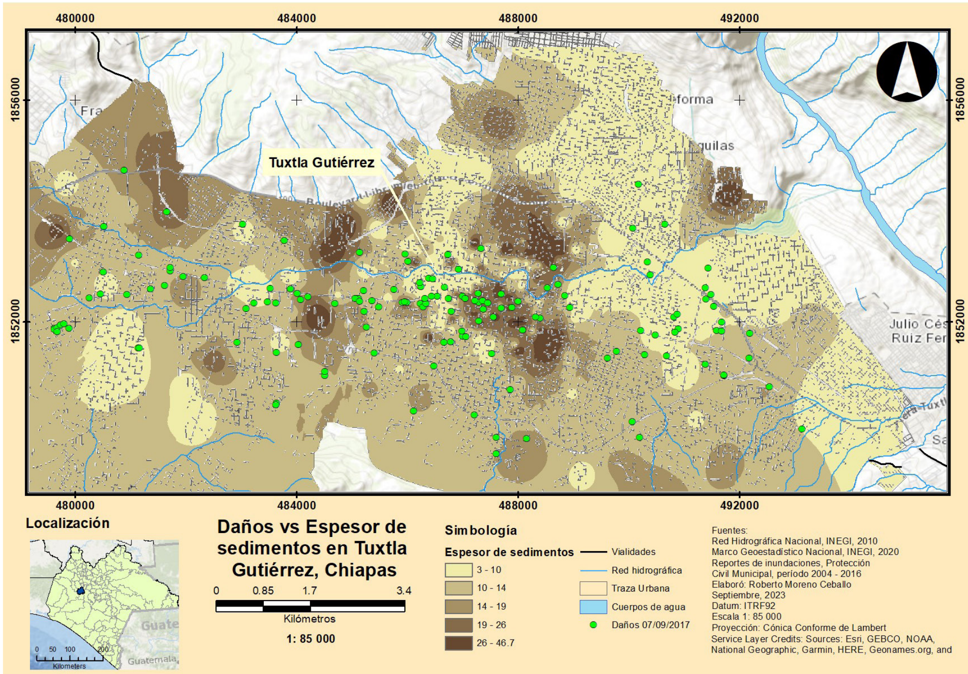


Figure 12. Thickness of sediments in Tuxtla Gutierrez, Chiapas

RESULTS

The development of sediment thickness maps and the analysis of seismic amplification in both urban areas allowed comparing the damage caused by earthquakes and, in turn, establishing a relationship with the areas of greatest impact. 198 blocks in Chiapa de Corzo were analyzed, and sediment thicknesses ranging from 7.12 m to 14.62 m were obtained (Figure 8). The city presents homogeneous constructive pathologies, which shows that the local conditions of the subsoil have been decisive in the location of the damage; it was also observed that the largest amount of these occur in areas between 8 and 12 meters thick of sediments and have been concentrated in the central area of the city and on the banks of the Grijalva River, that is, soft, poorly consolidated soils.

For Tuxtla Gutiérrez, thicknesses ranging between 3 m and 46.78 m were obtained (Figure 12) and a spatial correlation was made with the historical earthquake damage, finding that most of the damage is located in the central area and in the southwestern area of the city and is also located between 10 m and 20 m thick sediment. It is important to highlight the need to complement the results obtained in this work with current measurements located throughout the extension of the urban patch of both cities, since in recent years population growth has been considerable, also occupying areas considered at risk due to geological phenomena such as the southern slope of Tuxtla Gutiérrez (Paz-Tenorio, 2012).

CONCLUSIONS

Self-construction is a determining factor in the effects caused by the earthquakes that occurred in the study area. This has had consequences in groups with a high degree of marginalization of the population who, due to a lack of knowledge or resources, resort to this means to build their homes. Identifying existing threats and vulnerabilities in our community is an important task that will allow us to generate actions and ideas to reduce them through action plans.

The results presented here are part of an investigation related to the assessment of seismic vulnerability in the Metropolitan Area of Tuxtla Gutiérrez, using a methodology that allows preliminary zoning to be obtained using freely accessible information, which also allows it to be replicated in the rest of the cities of the MA.

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