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Seismic Hazard Analysis at Los Mochis, Sinaloa, Mexico

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Abstract

We studied the regional seismic hazard of the state of Sinaloa with emphasis on Los Mochis city, located in the municipality of Ahome, Sinaloa. Acceleration in rock was determined for different return periods (Tr = 475, 975, and 2475 years). We compared these results with the spectral accelerations proposed in the buildings seismic design Handbook by Earthquake of the Federal Electricity Commission (commonly applied in Mexico when absence of local regulations). It was observed that the seismic hazard was very sensitive to changes in the geometry of the source that contributes most to seismic hazard of the city. Particularly, PGA values were compared for 475 years, and it was observed that the increase in the PGA value due to that adjustment was approximately 35%. Additionally we performed a zonation study in the city, based on microtremors using single-station by applying horizontal-to-vertical spectral ratios (HVSR) analysis to 32 sites within the city. Results show low variations with higher values of natural period of resonance (To) in the southwest of the city. We explore a possible response for the entire valley by calculating a seismic hazard curve in terms of amplification factors.

Key words: seismic hazard, acceleration, seismic design, spectra, ambient vibration.

Resumen

Se estudió el peligro sísmico regional del estado de Sinaloa con énfasis en la ciudad de Los Mochis, ubicada en el municipio de Ahome, Sinaloa. La aceleración en la roca se determinó para diferentes períodos de retorno (Tr = 475, 975 y 2475 años). Comparamos estos resultados con las aceleraciones espectrales propuestas en el Manual de diseño sísmico de edificios por Terremoto de la Comisión Federal de Electricidad (comúnmente aplicado en México cuando no hay regulaciones locales). Se observó que el peligro sísmico es muy sensible a los cambios en la geometría de la fuente que más contribuye al peligro sísmico de la ciudad. En particular, los valores de PGA se compararon durante 475 años, y se observó que el aumento en el valor de PGA debido a ese ajuste fue de aproximadamente 35%. Además, realizamos un estudio de zonificación en la ciudad, basado en vibración ambiental utilizando una sola estación mediante la aplicación de análisis de relaciones espectrales horizontales a verticales (HVSR) a 32 sitios dentro de la ciudad. Los resultados muestran pocas variaciones con valores más altos de los periodos naturales de vibración (To) en el suroeste de la ciudad. Exploramos una posible respuesta para todo el valle calculando una curva de peligro sísmico en términos de factores de amplificación.

Palabras clave: peligro sísmico, aceleración, diseño sísmico, espectros, vibración ambiental.

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Introduction

Seismicity associated with subduction is the best known in Mexico since it has caused the largest earthquakes recorded. However, there is another region with high seismicity also associated with plate interaction but in a different way. The Gulf of California region including the Baja California peninsula forms a divergent boundary between the North American and Pacific plates. There is a relative movement between Baja California and the continent which is reflected in the existence of a system of transform faults and spreading centers that have generated large earthquakes and great damage on both sides of the gulf (Lonsdale, 1989). Seismicity in this region is distributed in the NW–SE direction along the axis of the Gulf of California, following the linear trend of these faults (figure 1).

Most earthquakes that occur in this region are moderate (magnitudes between 3 and 6 with depths close to 6 km (López Pineda et al, 2005). Among the regional moderate earthquakes

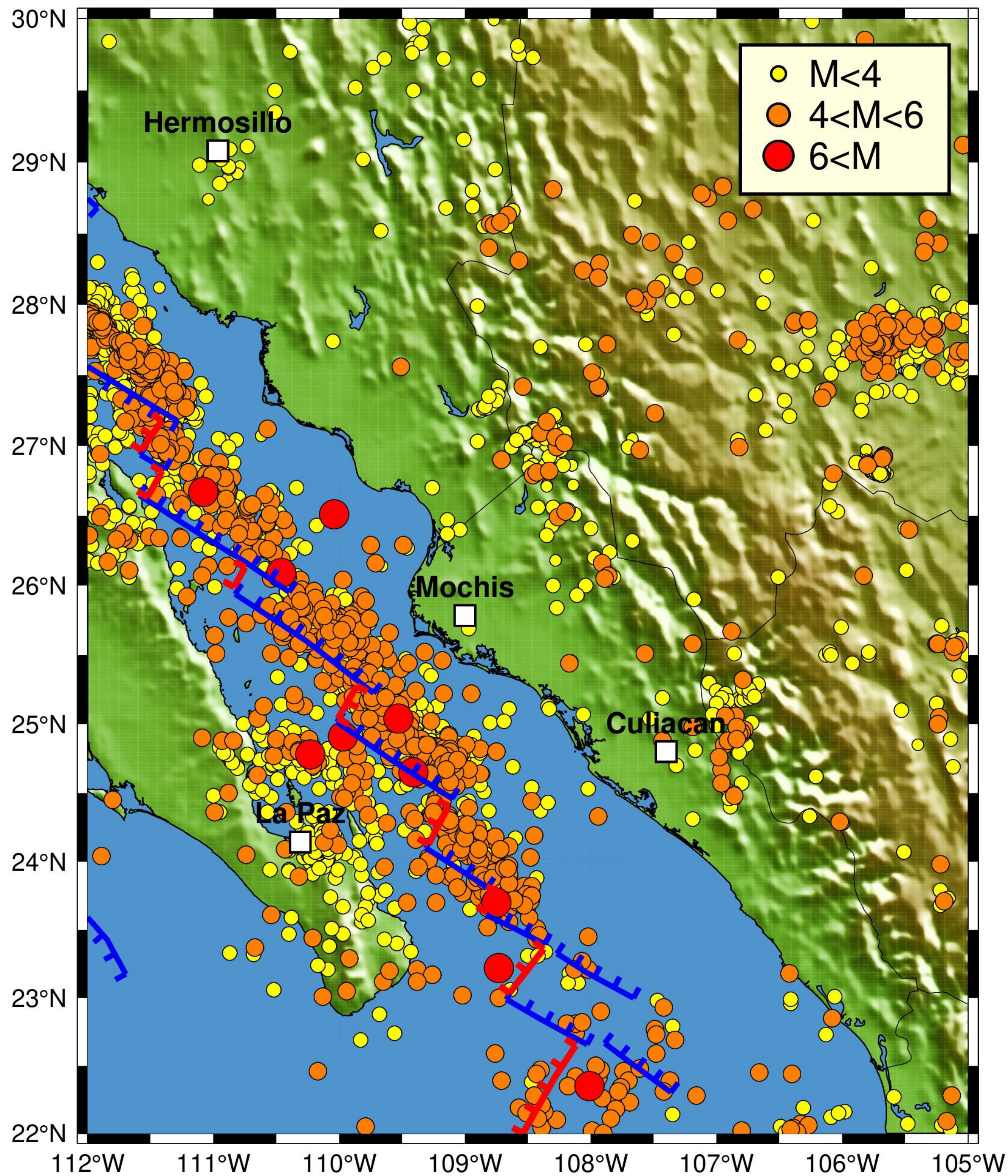

Figure 1. Tectonic setting and location of earthquakes. Blue lines indicate faults. Red lines indicate dispersion centers (Lonsdale, 1989). White squares indicate main cities in the area. Source, National Seismological Service of Mexico (SSN).

we can mention are the February 2005, (Mw 5.1), the September 2015 (Mw 6.7) and the July 2006 (Mw 5.8) earthquakes (Rodríguez et al, 2008, Rodríguez et al, 2010). However, there have also occurred larger earthquakes. The largest earthquake recorded in this area was the October 16, 1907 earthquake (Mw 7.1). Cities on both sides of the gulf are subject to the seismic hazard posed by earthquakes. Seismic records are essential for seismic hazard assessment which in turn can be used in civil engineering studies.

Mexico does not have a national regulation for seismic building design. Instead, two codes for seismic design are used throughout the country. The Complementary Technical Standards for earthquake design of Mexico City (NTC, 2017) and the buildings seismic design Handbook by the Federal Electricity Commission (MOC-CFE). The Mexican Society of Seismic Engineering included this topic as one of the main topics for discussion in their last conferences (SMIS, 2021, 2022), with the aim of moving towards the creation of a "Mexican Model Code for Seismic Design of Buildings".

For the elaboration of a realistic regulation for a certain locality, the observations of local damages occurred during earthquakes must be taken into account or, in the other hand, measurements of the mechanical characteristics of the soil in different parts of the city.

Mapping of site effects, also called microzoning, has been carried out in large cities around the world. A large number of these types of studies have relied on ambient vibration records given the ease and low cost with which the data can be obtained. Spectral ratios calculated between horizontal components relative to the simultaneously recorded vertical component (HVSR) have been used by Nakamura, (1989); Lermo and Chavez-Garcıa, (1994); Field and Jacob, (1995), among many others. It is now recognized that the HVSR technique generally provides a reliable estimate of the resonant frequency.

The city of Los Mochis in the state of Sinaloa, Mexico, has achieved the highest economic and geographical development in the region, and its population is considerable high.

A probabilistic evaluation of the seismic hazard with emphasis on the comparison with the seismic design spectra that is commonly used for the seismic design of new constructions in the region, was carried out in this paper with the purpose of generating useful information for decision making.

Seismic Hazard In Los Mochis Sinaloa

Seismic hazard assessment was carried out from a probabilistic approach mainly through a Poissonian model, which considers that each event occurs independently. The probabilistic methodology used in this study considers seismic sources or regions where earthquakes are known to have occurred and are expected to continue to occur. Seismic sources are those located at such distances that can generate significant seismic movements at a certain area the city of Los Mochis in this case. Estimation of seismic intensities, consider attenuation laws and equations that predict soil movement. In the probabilistic methodology, the uncertainties associated with seismic magnitudes, distances and intensities due to magnitude and distance are considered.

The basic equation of probabilistic seismic hazard was proposed by Cornell (1968) and taken up again by Esteva (1970). It establishes that the seismic hazard at a point of interest is defined by the sum of the seismic hazard associated with all seismic sources that influence that point.

The rate of exceedance of the intensities, at each site is calculated as:

$$v_i(a) = \sum_{j=1}^{n} w_{ij} \int_{M0}^{Mu} \frac{-d\lambda_i}{dM} \Pr(A > a \mid M, R_{ij}) dM \tag{1}$$

Where $Pr(A>a \mid M, R_{ij})$ is the probability that the acceleration "A" exceeds a fixed value "a", given the magnitude of the earthquake "M" and the distance "R_{ij}" between the source and the study site. wij is the weight assigned to each triangle in which the source has been divided. The integration is carried out from Mo to Mu which means that the contribution of all the magnitudes that each of the sources is capable of generating, is considered, being Mu and Mo the maximum and minimum magnitude respectively.

Finally, since in general for each calculation site there is more than one source contributing to the total seismic hazard level

$$v(a) = \sum_{i}^{n} v_i(a) \tag{2}$$

This model has been implemented in MOC-CFE (2008) which includes a computer package called PRODISIS. On the other hand, the Institute of Engineering, UNAM, developed a software called "Seismic Hazard in Mexico" or PSM2004. Both include these equations in their calculations.

Modeling begins with the definition of seismic sources which contribute to seismic hazard of a region. They can be point sources or seismic areas defined by geometric forms such as polygons. Seismic hazard estimation of the region is the result of the sum of all contributions (Zúñiga *et al.*, 1997, Kramer, 1996). We use as a fundamental reference, the different versions of the MOC-CFE since they include seismic hazard studies of different sites and different types of structures along the country. Additionally, we used works related to the seismic hazard of Mexico published in a complementary way to the CFE Handbook (Ordaz *et al.*, 2004, Ordaz *et al.*, 2015; Aguilar-Meléndez *et al.*, 2017).

Based on the geographical distribution of seismic hypocenters of earthquakes and tectonic features, MOC-CFE (2015a, c) defined geometric areas as seismic sources along the country (figure 2a).

For a first approximation of seismic hazard of Los Mochis, we considered that all the seismic sources, as defined in MOC-CFE, contributed. After a quick analysis we observed that only those in light gray and numbered in figure 2b actually contributes.

Each area is characterized by seismicity parameters such as higher magnitude of events that can occur within the area (*Mu*), lower magnitude (*Mu*), exceedance rate per year of earthquakes (λ), ratio between large and small earthquakes (β); variations of β, given by a coefficient named *C*, mean value of return periods (*Med*(*T*)), and standard deviation of acceleration of the characteristic event (σ_M) and the queer event (σ). Table 1 shows the seismicity parameters of these seismic sources.

Additionally, we used two attenuation laws. One for cortical earthquakes proposed by Abrahamson & Silva (1997), and the Atkinson & Boore's law (2006) as those are the most representative for the zone due its tectonic features (Table 2).

Seismic hazard can be estimated in a probabilistic mode

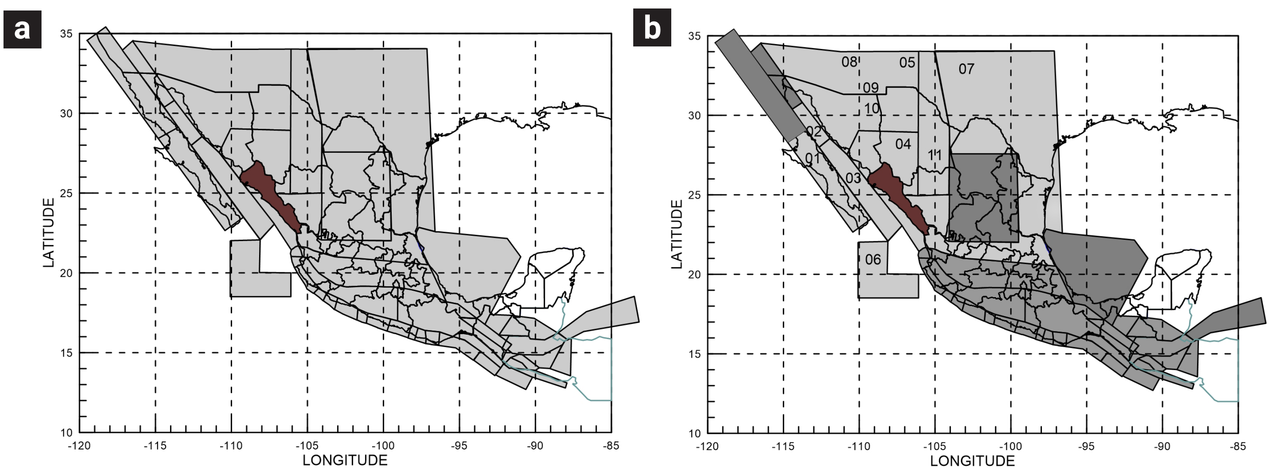

Figure 2. (a) Seismic sources used in MOC-CFE (2015a, c) for the entire country. (b) Seismic sources that contribute to the seismic hazard of Los Mochis (numbered sources).

Table 1. Parameters for seismic sources

Number	Name *	Mo	λ(Mo)	β	C(β)	Mu	σ
F01	SBCINTRA	4.50	1.21	0.933	0.036	5.80	0.00
F02	CBCINTER	4.50	0.726	1.637	0.168	7.40	0.40
F03	SBCINTER	4.50	2.09	1.674	0.082	7.20	0.60
F04	SM	4.50	0.116	2.880	0.03	5.60	0.00
F05	BR	4.50	0.150	2.880	0.03	5.60	0.00
F06	PRB	4.50	3.410	1.736	0.088	7.20	0.00
F07	DS01	4.50	0.607	2.880	0.03	5.60	0.00
F08	DS02	4.50	0.175	2.880	0.03	5.60	0.00
F10	BGR	4.00	0.500	2.00	0.00	7.40	0.00
F11	WCH	4.50	0.112	2.88	0.03	6.40	0.00

Number	Name	Med (T)	σM	Mo	σ
F09	BTC	500	3.0	7.40	7.60

* SBCINTRA=South Baja California Intraplate; CBCINTER=Center Baja California Interplate; SBCINTER= South Baja California Interplate; SM=Sierra Madre; BR=Basin and Range; PRB=Pacific-Rivera Boundary; DS=diffuse seismicity; BGR=Bavispe Gutemberg-Richter; BTC=Bavispe Characteristic earthquake; WCH=West Chihuahua.

Table 2. Attenuation laws used.

Number	Name	Model	Attenuation law
F01	SBCINTRA	GR	Abrahamson & Silva
F02	CBCINTER	GR	Abrahamson & Silva
F03	SBCINTER	GR	Abrahamson & Silva
F04	SM	GR	Abrahamson & Silva
F05	BR	GR	Abrahamson & Silva
F06	PRB	GR	Abrahamson & Silva
F07	DS01	GR	Abrahamson & Silva
F08	DS02	GR	Abrahamson & Silva
F09	BTC	GR	Atkinson & Boore
F10	BGR	TC	Atkinson & Boore
F11	WCH	GR	Abrahamson & Silva

* GR=Gutemberg-Richter; TC= characteristic earthquake

via exceedance probability. It is based on a modified Gutemberg-Richter relation

$$Pe(a,T \mid M, R)=1\text{-exp}\,[-\Delta\lambda(M)T \cdot p_i\,(a \mid M, R)] \qquad (3)$$

Where *Pe* is the exceedance probability of the hazard intensity level a, given that an event with magnitude *M*, occurred at a distance *R* from the site of interest, and is the poissonian magnitude exceedance rate associated to the magnitude range characterized by the magnitude *M* depends on table, the parameter which relates the proportion between large a small events in the original Gutemberg-Richter relation. The total contribution of the seismic source is calculated by equation (1).

The contribution of each source to the seismic hazard of Los Mochis in terms of exceedance probability for 50 years, was calculated using the CRISIS2015 software (Ordaz *et al.* 2015). It is shown in figure 3. It can be seen that the highest exceedance is due to the source called South Baja California Interplate (F03). For example, for a 58 gals Sa, the seismic source F03 contributes about 97% of the total exceedance rate, a trend that is maintained for higher seismic accelerations.

Considering physical characteristics of an area, spatial distribution of seismic sources and their contribution to the seismic hazard of that area, attenuation laws and characteristic vibration periods of civil structures among other parameters, we can build a spatial distribution map of probable ground motion acceleration due to the occurrence of an earthquake called designed seismic event with a specific return period. Conventional civil structures are usually designed for seismic events with return periods of 475 years but special structures are designed for larger return periods.

We calculated seismic hazard maps for Ahome municipality for which Los Mochis is the main city. PGA maps shown in figure 4, were calculated for return periods of 475, 975 and 2475 years.

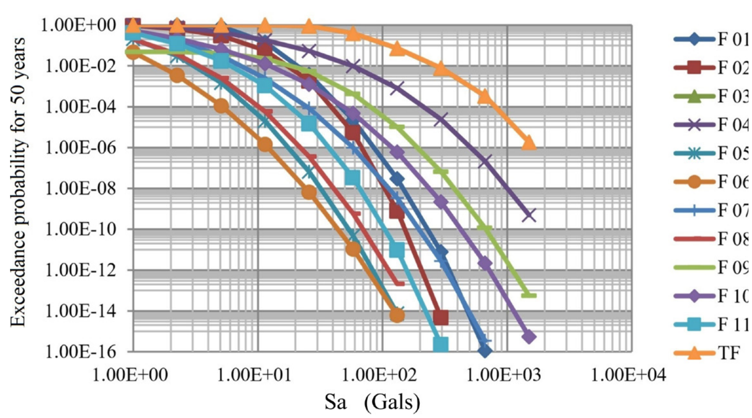

Figure 3. Contribution of each source to the seismic hazard of Los Mochis.

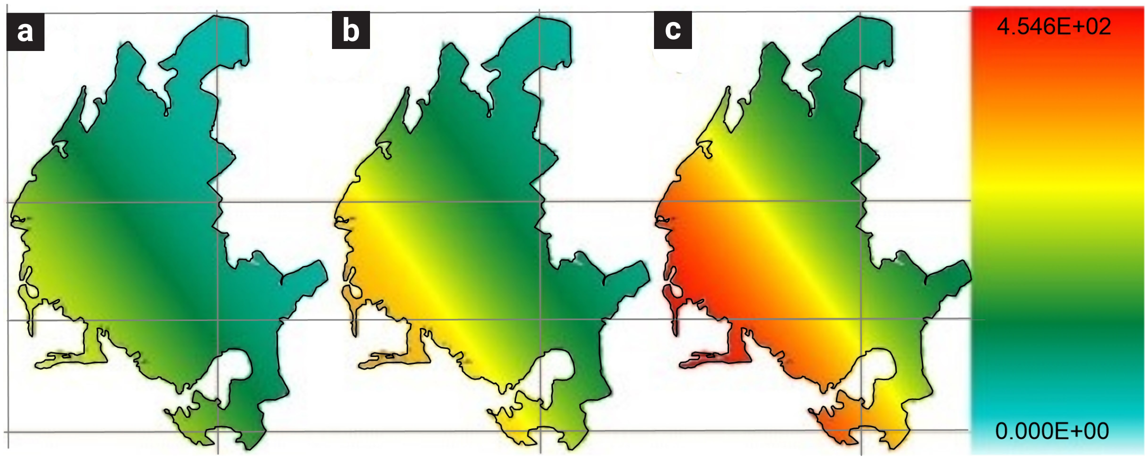

Figure 4. Hazard maps for Ahome municipality. Acceleration color code is in gals for return periods of 475 (a), 975 (b) and 2475 (c) years respectively.

Influence of changes in geometry of sources

Several modifications and additions of seismic sources have been incorporated in the MOC-CFE (2015a, c) since those proposed by Ordaz *et al.* in 2008 (Figure 5a). These updates result in modified seismic hazard values of some areas. One of the updates consisted of the fragmentation of existing sources into several independent sources as shown in Figure 5b.

We recalculated the exceedance rate of intensities for each seismic source considered in figure 5b and compared the contribution of each source, with that from the sum of all them (TF) for a given value of pseudo acceleration (Sa) and period (Te). The results are shown in Table 3.

Values suggest that the new seismic sources and changes considered in the MOC-CFE (2015a, c) are not relevant for the area of study. At the same time, they show that source 03

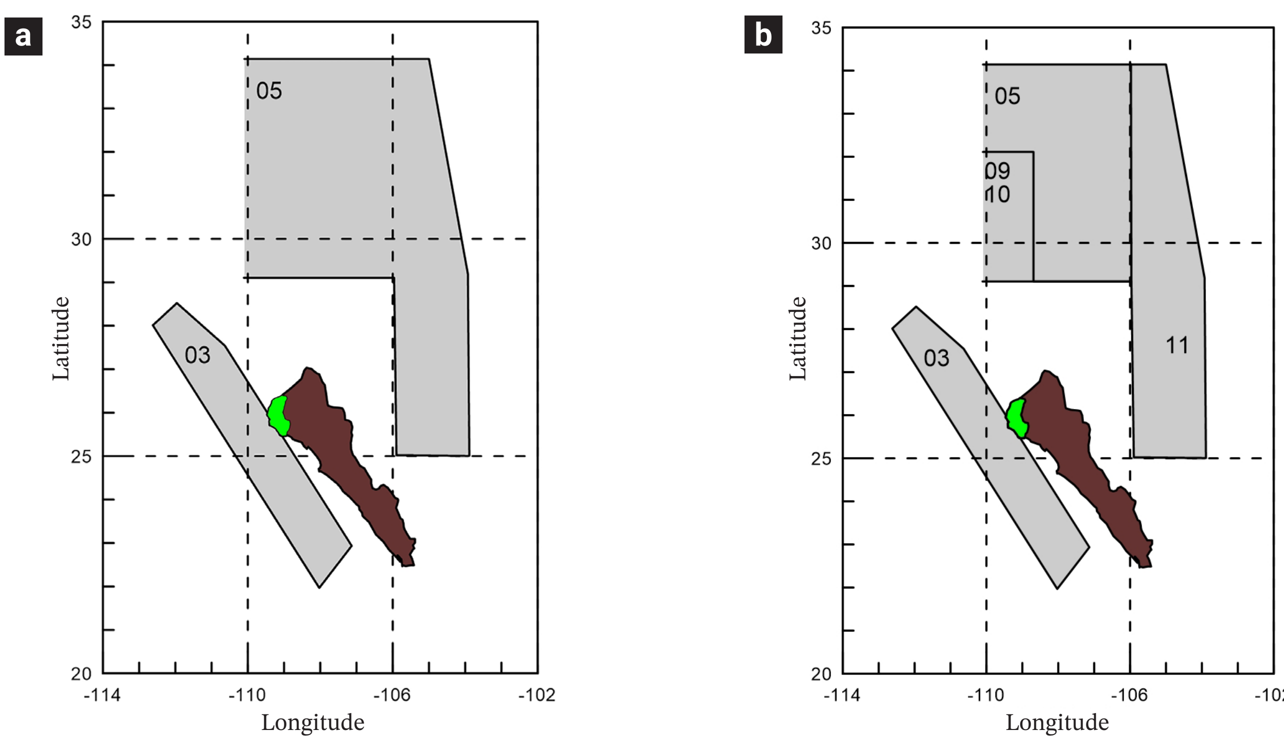

Figure 5. Seismic sources in the area of study. (a) from Ordaz *et al.* (2008) and (b) MOC-CFE (2015). Green area indicates the Ahome municipality.

Table 3. Contribution of sources to the seismic hazard for Los Mochis.

Te (sec)	Sa	F03	F05	F09	F10	F11	TF
0.01	113.00	98.17%	0.00%	0.06%	0.01%	0.00%	100.0%
0.15	270.00	98.26%	0.00%	0.01%	0.00%	0.00%	100.0%
0.30	258.00	99.28%	0.00%	0.02%	0.00%	0.00%	100.0%
0.50	202.00	99.57%	0.00%	0.05%	0.01%	0.00%	100.0%
1.00	137.00	99.53%	0.00%	0.06%	0.01%	0.00%	100.0%
2.00	80.80	98.79%	0.00%	0.09%	0.01%	0.00%	100.0%
3.00	44.10	98.23%	0.00%	0.23%	0.01%	0.00%	100.0%

defines almost the totality of the seismic hazard for the city of Los Mochis, Sinaloa.

On the other hand, we compare in table 4, the PGA values obtained using PRODISIS v4.1 (2015) with those obtained from the 2004 study (PSM2004) for the city of Los Mochis for a return period of 475 years which, as mentioned before, is a standard return period for common structures design. We can observe a difference of about 35% for the different structural periods shown in the table.

The reason for this difference is mainly due to an adjustment made to the geometry of the seismic source of South Baja California Interplate. The 2004 did not include a part of the state of Sinaloa (figure 6). This inclusion affects specifically Ahome municipality. The modification of the geometry of the seismic source was due to the seismicity identified in the region (Leonardo, 2012; Castro *et al.*, 2021).

Estimation of Uniform Hazard Spectra (UHS) did also change due to the mentioned update. For comparative purposes, we obtained the UHS for a return period of 760 years (6.35%

Table 4. Spectral accelerations for Los Mochis, Sinaloa

PSM 2004		PRODISIS (2015)	
Te (s)	Sa (gals)	Te (s)	Sa (gals)
0.01	81.18	0.01	108.61
0.15	193.00	0.15	257.79
0.30	196.00	0.30	248.00
0.50	160.00	0.50	194.77
1.00	112.00	1.00	133.21
2.00	65.90	2.00	78.23
3.00	37.10	3.00	43.72

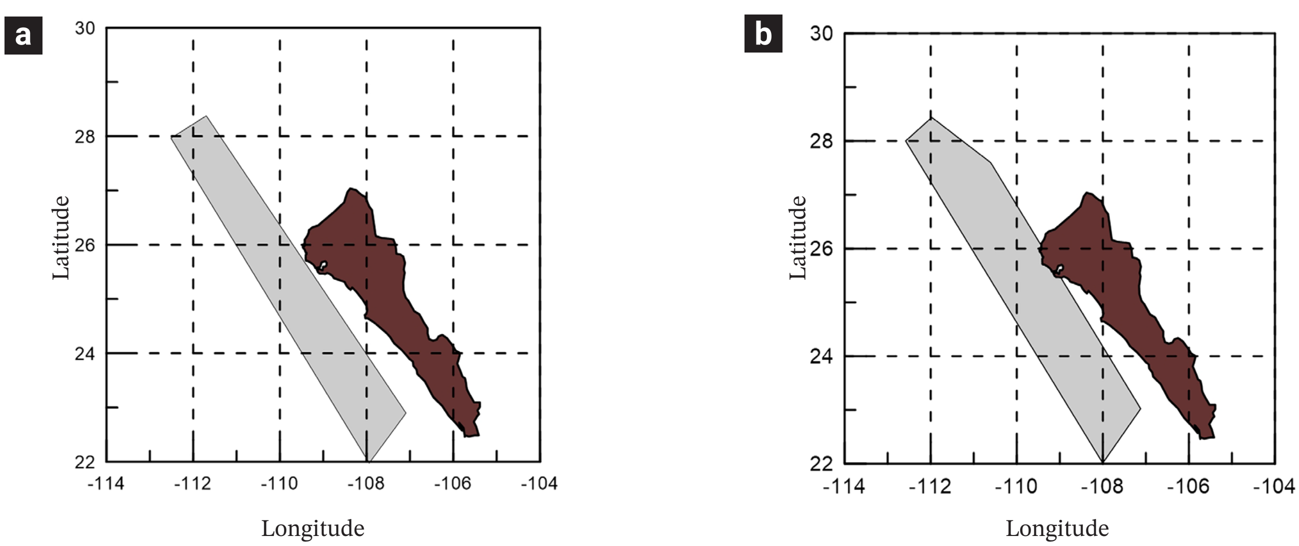

Figure 6. Geometry of the seismic source called South Baja California Interplate. (a) in 2004 and (b) in 2015.

of probability of exceedance in 50 years) from three different information sources: The PRODISIS, 2008, 2015, and the CRISIS20015 software (Figure 7)

Using CRISIS2015 software, we obtained UHS for return periods of 475, 975 and 2475 years. It is possible to observe from these spectra that between the structural periods of 0.15s and 0.40s there are important spectral accelerations in all cases (figure 8). These periods usually correspond to structures of low to medium height.

Site effects

Damage distribution during large earthquakes is frequently controlled by site effects. Subsoil impedance contrasts can significantly amplify the shaking level, as well as increase the duration of strong ground motion. We begin with mapping the dominant period distribution along the city and then, as the city is over alluvial soil we explore an hypothetical response of the entire valley.

HVSR

Spectral ratios of horizontal components relative to the vertical recorded simultaneously have been widely used to determine site response from ambient-vibration records. The records of 32 sites within the urban area of Los Mochis were analyzed (Figure 10). A Kinemetrics ETNA recorder with triaxial accelerometers and a sampling rate of 100 samples per second was used. The open source Geopsy (Geophysical Signal Database for Noise array Processing) software (Wathelet et al, 2020) was used for this analysis.

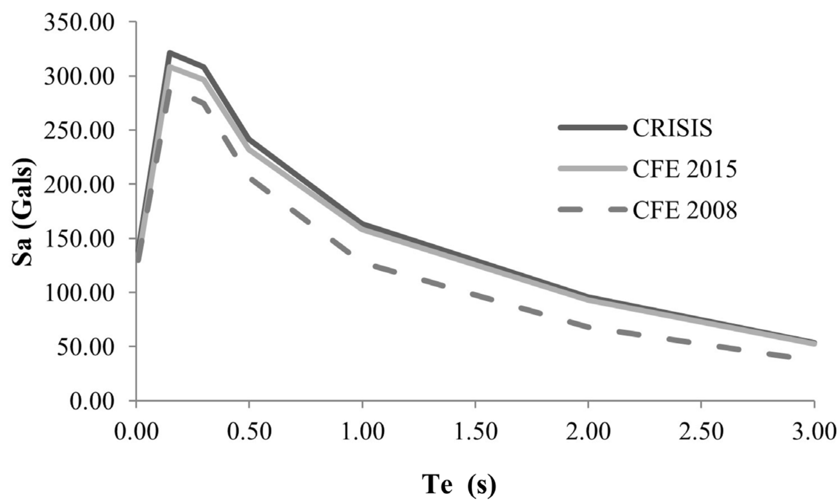

Figure 7. Uniform Hazard Spectra for return periods of 760 years for Los Mochis, from different sources.

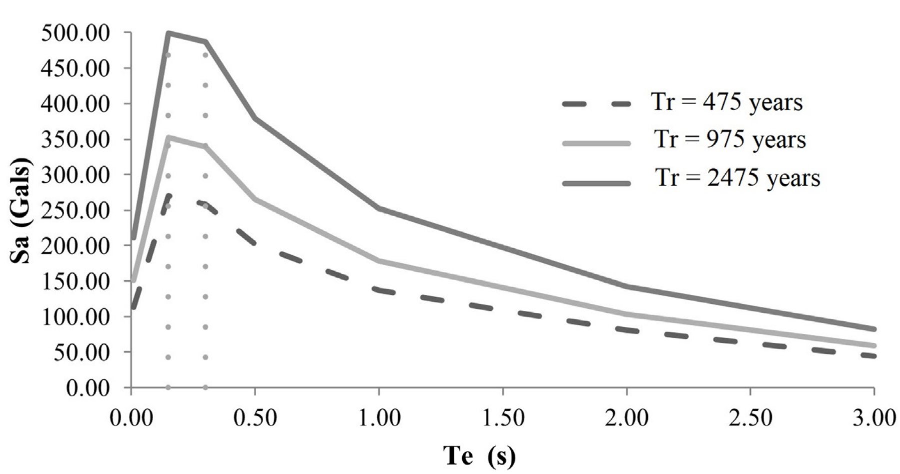

Figure 8. Uniform Hazard Spectra for Los Mochis for return periods of 475, 975 and 2475 years (CRISIS2015).

At each site we obtained two or more ambient vibration records (in most cases were three) with durations of 1 to 3 minutes. In each record, we selected 15 seconds windows which showed the fewest transient signals and the noise appeared more stationary (Figure 9a). The program calculates the spectral ratio for each window and returns the mean value and standard deviation (figure 9b). We choose the average of all the HVSR obtained and identified period value and maximum amplitude at the site (Figure 9b).

Once the dominant periods for all points were estimated, they were used to build a contour map for the city as shown in Figure 9.

We observed dominant periods between 0.4 and 0.5 seconds within the city. As the city is built entirely over an alluvial soil, we did not expect great variations. Nevertheless we observed slight higher values (around 0.6 seconds) towards the southwest of the city.

In order to determine a possible response of the entire valley in the presence of an earthquake,we used the relative amplification derived from the single-station microtremor measurements, analyzed using HVSR.

Seismic Hazard

An analysis of seismic hazard, in terms of amplification factors was carried out.

Values of maximum relative amplification, as measured from the HVSR, vary between 2 and 4.2, although the majority are around a factor of 2. Given this variation and the fact that HVSR of microtremor records usually underestimates amplification (Bard, 1999), we included two possible amplification factors to estimate seismic hazard curves for Los Mochis using CRISIS2015 software (figure 10).

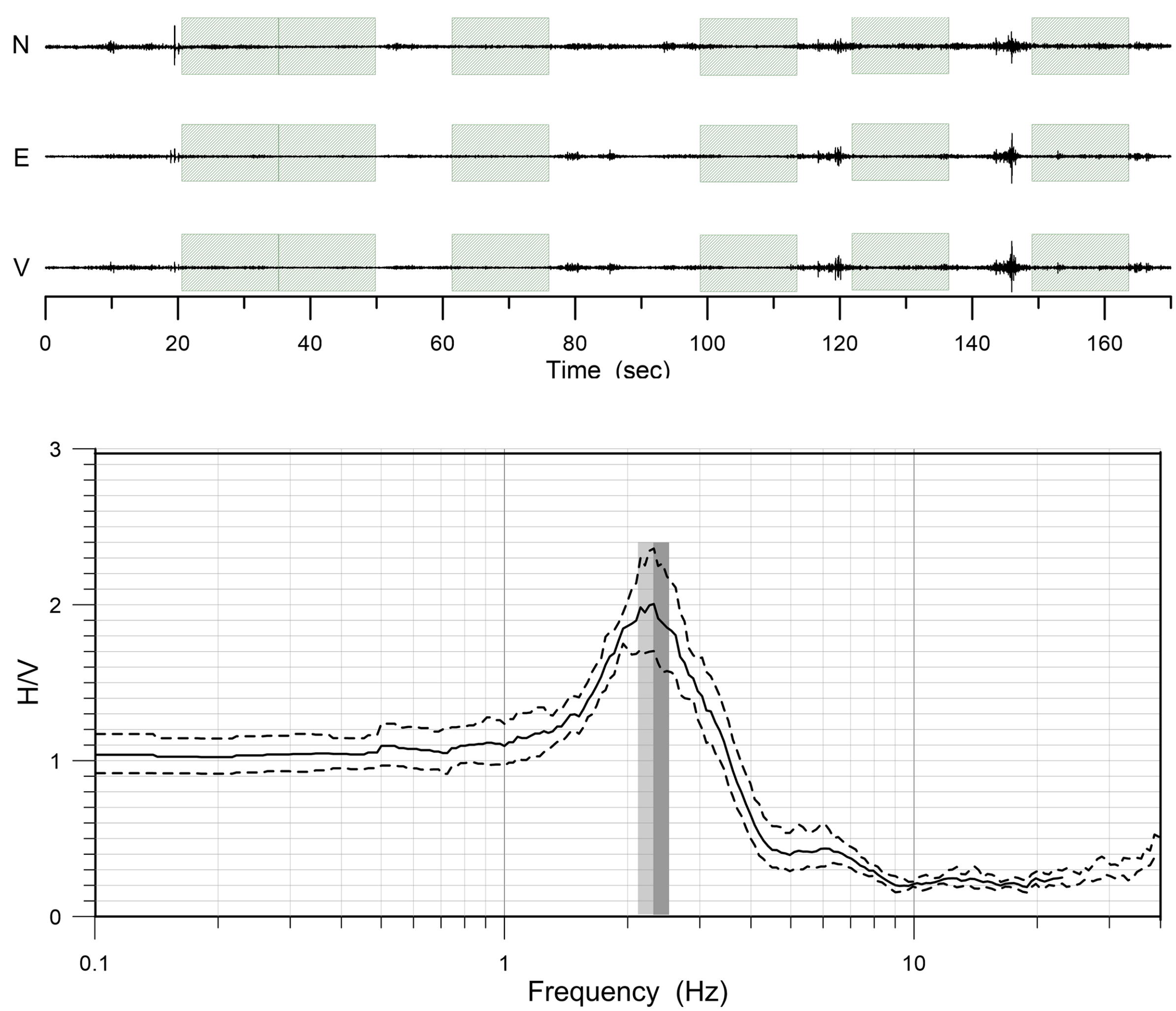

Figure 9. Example of a three component record (a) and spectral ratio (b) obtained at site P01. Green rectangles show the windows used. Shadowed rectangles in (b) show the maximum amplitude. Dashed lines indicate standard deviation of the spectral ratios given by the different windows used.

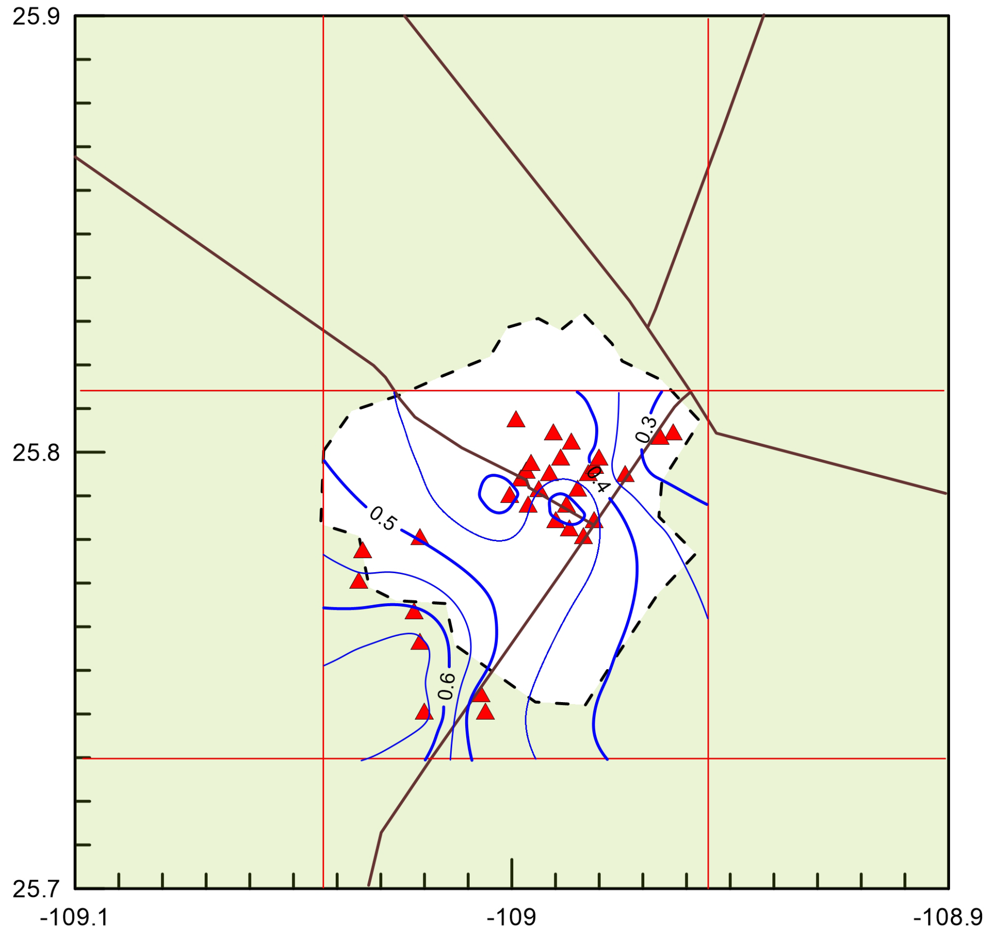

Figure 10. Contour map of dominant periods for Los Mochis city (blue lines). Triangles indicate the sites of measurements of ambient noise. Brown lines indicate the main roads. Dashed line indicate city limit.

According to these results, the value of acceleration in rock for a return period of 475 years is equal to 113 gals while for soft soil (alluvial) the value of the acceleration for that same return period is between 126 and 475 gals depending on the amplification factor of 2 or 4.2, respectively.

These results, show the importance of considering site effects in estimating the seismic hazard. It is worthy to mention that the value of 113 cm/s2 obtained for a return period of 475 years for Los Mochis, is similar to the 108.61 cm/s2 obtained by PRODISIS v4.1 (CFE, 2015b) for the same city.

Using an amplification factor of 4.2, which was the largest amplification we found, a seismic hazard map was obtained for the municipality of Ahome (Figure 11).

It can be seen that accelerations shown in the map obtained considering firm rock changes drastically when compared with those in the map with uniform amplifications of 4.2, for a return period of 475 years. This observation confirms the importance of conducting further studies to determine site effects in Ahome.

Conclusions

We calculated Uniform Hazard Spectra for Los Mochis and seismic hazard maps for Ahome municipality for which Los Mochis is the main city from a probabilistic approach for return periods of 472, 975 and 2475 years.

It was observed that an adjustment made to the geometry of the seismic source of South Baja California Interplate that include a part of the state of Sinaloa, meant a difference of 35% in seismic PGA.

We performed a microzonation study in the city, based on microtremors using single-station by applying horizontal-to-vertical spectral ratios (HVSR) analysis. Results show low variations with slightly higher values of To in the southwest of the city.

The attempt of estimating the response of the entire valley in the presence of earthquakes, show the importance of taking into account the site effects, since the accelerations that occur in soil can be significantly larger than those that occur in rock.

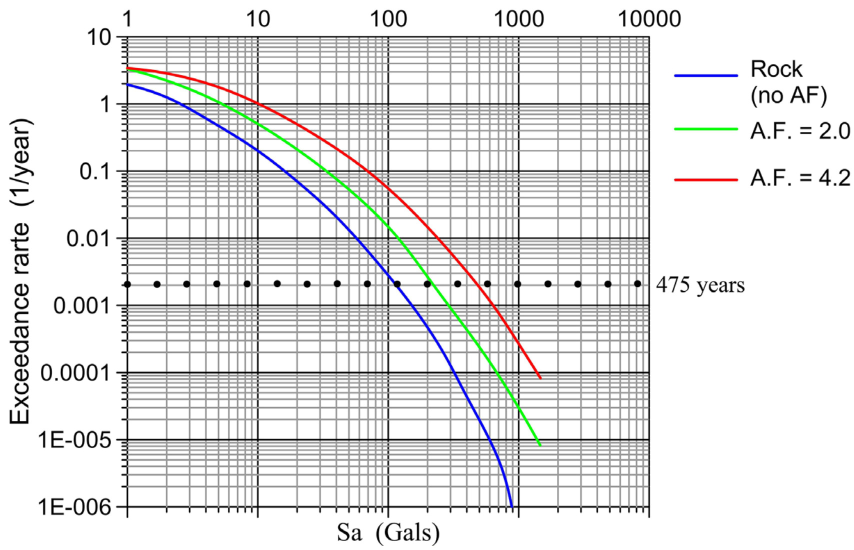

Figure 11. Seismic hazard curves for Los Mochis in terms of amplification factors.

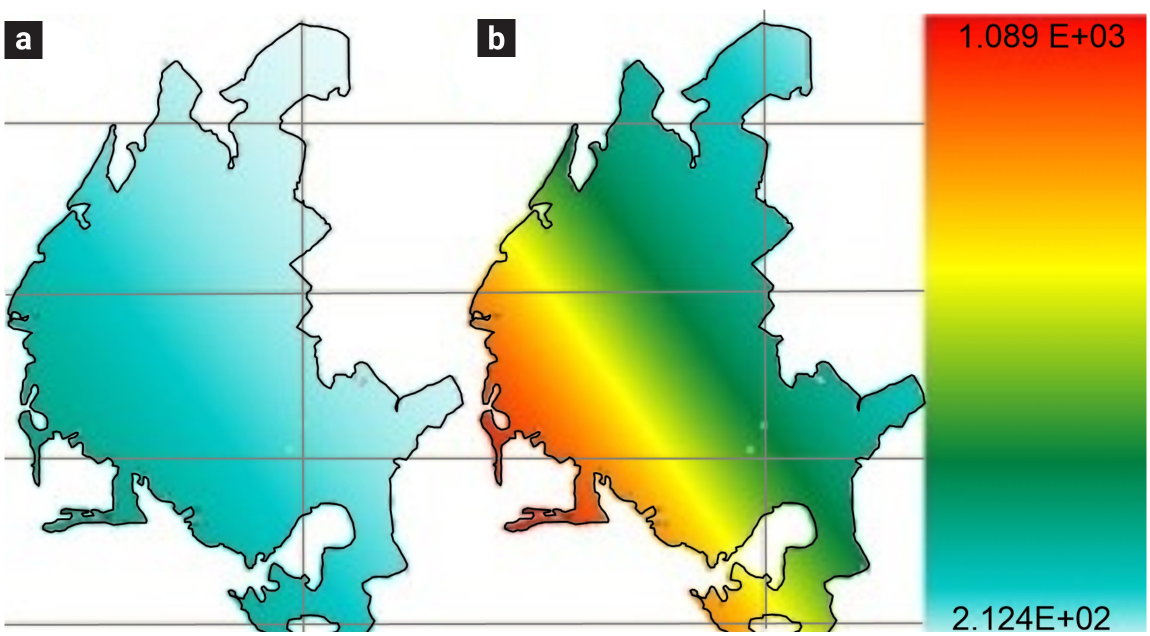

Figure 12. Seismic hazard map in terms of accelerations (gals). (a) for rock and (b) for soft ground considering 4.2 as amplification factor.

Underestimating spectral accelerations can significantly reduce the safety of structures.

More site effect studies should be done in Los Mochis and other main cities of Sinaloa state to improve the dataset available but it is more important that new resources can be applied in order to elaborate seismic normative for the main cities of Mexico. This condition is essential in order to increase the resilience of the Mexican cities.

New buildings should be subject of thorough studies of seismic engineering.

It is essential to promote the execution of seismic hazard studies of each region of our country, so that these studies include sensitivity analyses that contribute to identifying the most appropriate parameters, to consider the seismic particularities of each region.

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