

Article

Site-Specific Spectra for the City of Mexicali, Mexico, Obtained from April 2010 Earthquake Records

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Abstract: The April 2010 earthquake ($M_w = 7.2$), which occurred about 40 km to the southeast of the city of Mexicali, Mexico, caused significant damage to buildings. To improve knowledge of the seismic response of the soil due to the occurrence of earthquakes, a response spectrum at 5% damping was calculated. A comparison between the spectral ordinates obtained in this study and the spectra proposed by the regulations of the Federal Electricity Commission (CFE for its acronym in Spanish) in its seismic design for civil works manual, which is currently used as the design standard throughout the country, was made. We calculated response spectra using records from the April 2010 earthquake and a stratigraphic profile of the city to calculate a transfer function. We first corrected the records for site effect due to stations being over sedimentary soil, and then used them as Green functions to perform a numerical simulation of propagation through the stratigraphic profile to obtain a simulated surface record from which response spectra were calculated. Additionally, ambient seismic noise was measured at the same site to get the dominant period (T_0). We observed that the transfer function was similar to the spectral quotient up to 5 Hz and that T_0 calculated in both ways gave similar values. The comparison suggests that the design spectrum of the CFE regulation can be considered as a representative spectrum for Mexicali for periods greater than 1.3 s, but not for the zone of short periods.

Keywords: site-specific spectra; Mexicali; response spectra; earthquake; seismic records; April 2020 earthquake

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1. Introduction

Some earthquakes have significantly damaged several cities in the last two decades. For instance, the Japan earthquake of 1 January 2024 [1–3], the Turkish earthquakes of 6 February 2023 [4–8], and the Mexican earthquake of 19 September 2017 [9–12]. In all the previous cases, each earthquake triggered significant damage. Considering only these cases, the Turkish earthquakes were the events that triggered the most major damage, and in which a more substantial number of people died. In these three countries where earthquakes occurred, a portion of the societies know earthquakes are common natural events. However, the preparation for reducing the risk due to future earthquakes differs in these countries, because each has different priorities and socioeconomic conditions. Notably, in the Mexican case, it is possible to affirm that some groups of society recognize that we

need to increase efforts to improve our ability to support against future earthquakes with significant potentials for seismic damage.

Seismic damage in buildings depends on different factors. Still, to simplify the problem, we can mention that seismic damage in a building is mainly a function of the building's vulnerability and the features of the ground motion. Every day, we have more knowledge about building buildings that can withstand or not receive damage during and after a significant earthquake. However, this new knowledge does not resolve the complete earthquake-related problem, because we still have buildings built with old seismic codes. And, because we also have cases where new buildings or houses are being built without using modern seismic codes. Therefore, different governments have made important efforts to contribute to offering economical resources to retrofit buildings with high vulnerability or seismic risk.

Concerning the type of seismic damage in buildings in the three cases mentioned previously, it is possible to say that, in general, the damage occurred in buildings with specific vulnerabilities. For instance, the vulnerabilities could be related to some of these conditions: (a) the seismic code used to design the buildings is not recent, (b) the presence of building errors or deficient quality of materials, (c) modification of the original project without appropriate structural analysis, etcetera. Therefore, it is not easy to answer the following question: how can we obtain the economic resources required to retrofit the buildings that we know have significant vulnerability?

On the other hand, significant projects have been developed worldwide to understand more about the features of seismic ground motions. If we know, with more certainty, the features of the next earthquakes, then we have a better chance of determining the probable seismic behavior of our buildings and modifying or designing them to withstand those major earthquakes.

To understand more about the damage after an earthquake, it has been possible to identify that, in general, the damage distribution due to large seismic events depends on several factors, among which site effects stand out. The impedance contrast between the surface layers and the basement can significantly amplify the waves traveling through the subsurface and lengthen the duration of the ground motion.

It is essential to highlight that the city of Mexicali has been affected by significant earthquakes. For instance, Figure 1 shows the epicenters of earthquakes in the Mexicali region and its surroundings since 1976.

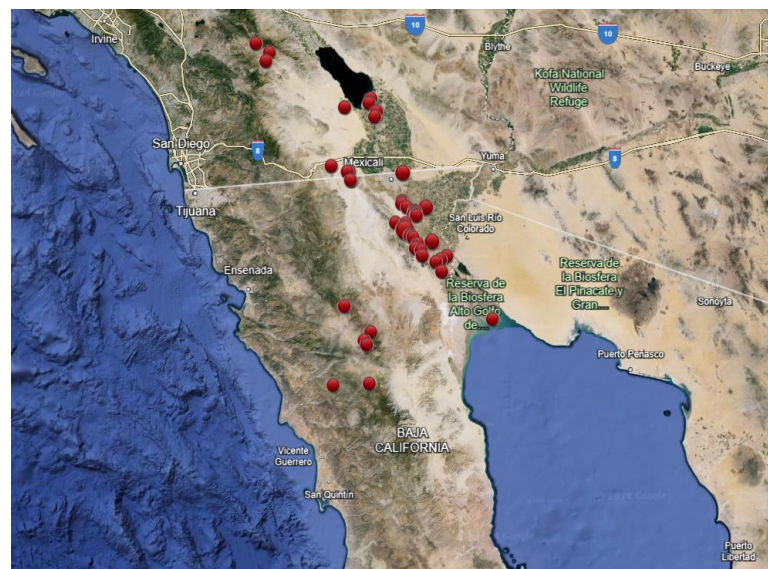


Figure 1. Epicenters of earthquakes around Mexicali, since 1976, with a magnitude greater or equal to 5 that were recorded in the CICESE Red.

Mexicali is an important city in Mexico since it is one of the common ways to travel to the USA. This city is also the capital of the state of Baja California, Mexico, with a population of more than 800,000 inhabitants. Mexicali is located in one of the most active seismic zones in the country, with more than 150 events with magnitudes greater than 5.0 Mw in the last 100 years. The last major earthquake that shook the city and the entire northwest region of the country and the southwest of the United States occurred on 4 April 2010 (7.2 Mw, Figure 2), about 40 km southeast of the city, causing significant damages. In the city alone, at least 103 buildings with structural damage or which had partially collapsed were reported [13,14].

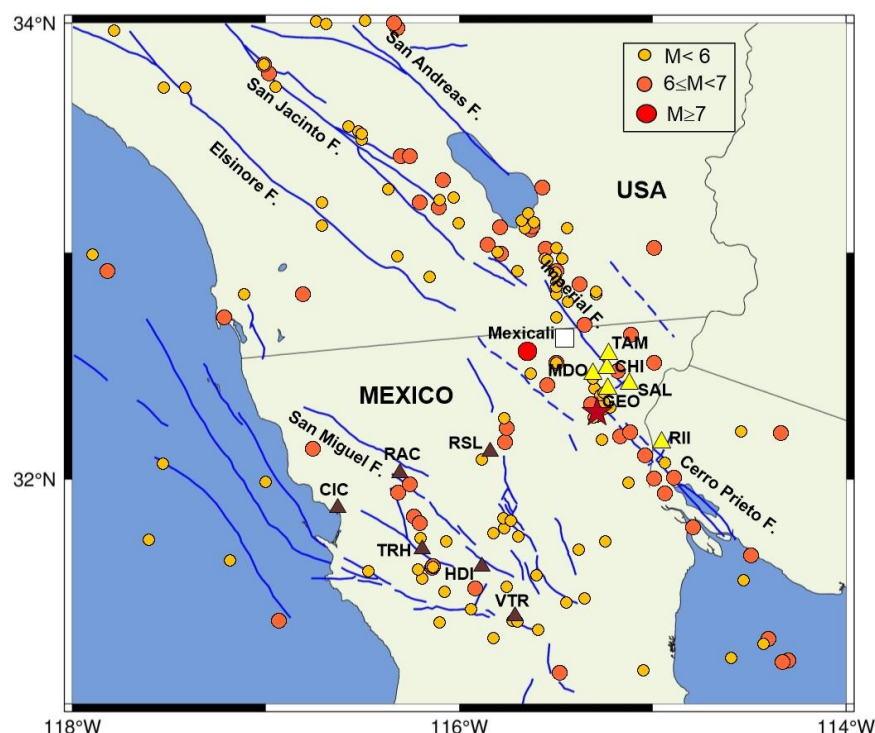


Figure 2. Location of the seismic stations used in this study. The yellow triangles indicate stations on sediments, and the brown triangles indicate stations on rock. The star represents the epicenter of the 4 April 2010, earthquake (Mw 7.2), and the rectangle represents the city where the environmental vibration measurements and geotechnical survey were conducted. Epicenters of events with magnitudes greater than 5 in the last 100 years are shown in circles. Tectonic faults are indicated in blue.

Among the recommendations made in 2010 by the Earthquake Engineering Research Institute (EERI) in its earthquake report [13] is improving the seismic design of structures, especially for schools and hospitals.

Mexico lacks national building regulations. Instead, two seismic design codes are generally used: the complementary technical standards of seismic design for Mexico City [15–17], which are primarily used in the cities around Mexico City, and the earthquake design for civil works manual of the Federal Electricity Commission (MOC-CFE) [18].

Design spectra established in local building regulations must be as realistic as possible. They are intended to contribute to ensuring the integrity of the structures in the event of a major earthquake. To do so, they must be subject to updates provided by analysis of real data of the site of interest.

The seismic elastic response spectrum can be determined using different procedures according to the building code chosen. However, some building codes recognize that the “site-specific spectra offer accurate and less conservative acceleration values” [19].

Several countries have issued seismic design regulations based on the response spectrum. For example, Peru [20] and Ecuador [21] have issued official regulations to reduce

the ordinates of the response spectrum through specific parameters that must be considered when designing civil structures.

A procedure to verify if a building code is appropriate for modeling the seismic behavior of buildings is to compare the behavior of a structure considering a site-specific spectrum curve versus the behavior of the same structure considering the elastic spectrum curves of the seismic code. This procedure was recently applied using data from the terrible earthquakes in February in Turkey. Notably, in a recent work, the authors compared the behavior of buildings using the elastic spectrum curves in TBEC-2018 and the behavior using a site-specific spectrum curve [22]. According to the results of this work, when they used the site-specific spectrum, they obtained significantly more seismic damage; for instance, the damage could be increased to 43% in the case of the beams [22]. This kind of result confirms the importance of obtaining site-specific spectra.

In the present study, we calculated synthetic response spectra at 5% critical damping for the city of Mexicali based on the acceleration records of the April 2010 earthquake. We compared them with the design spectra of the MOC-CFE [18], which is the one used in the area due to the absence of official local regulations.

2. Determination of the Site-Specific Spectra

2.1. Regional Tectonics and Seismicity

The main tectonic feature of the area is the boundary between the Pacific and North American plates. This boundary is formed by a series of seismically active faults from the northern shores of the Gulf of California, beginning with the Cerro Prieto fault to the south, crossing sedimentary basins such as the Mexicali Valley, the Altar Basin, and the Salton Sea, and connecting with the Elsinore, San Jacinto, and San Andreas faults to the north (Figure 2).

There are also fault systems adjacent to this boundary. The rupture area of the 2010 earthquake occurred in one of these zones between the El Mayor and Cucapah mountain ranges on the southwestern boundary of the Pescadores fault [23].

The western side of the Sierra Cucapah is controlled by an essential active dextral fault with a small normal component called the Laguna Salada fault [24].

According to [23], “The background seismicity shows prominent geographical trends in the northeast and northwest directions”. Notably, the authors of this manuscript [23] describe the region’s seismicity in terms of bands. They mentioned that the longest bands of seismicity reach more than 20 km long and that faulting features produce two types of focal mechanisms: right-lateral strike-slip and normal focal [25].

During the decade from 2001 to 2010, the background seismicity in the Baja California region was high and complex. A significant number of swarms and mainshock-aftershock sequences occurred, and in some cases, the swarms were associated with geothermal areas [23,26].

2.2. Accelerations Records

We analyzed the seismic records of all the available public stations (the Mexican stations) that recorded the 4 April 2010, earthquake. Stations are 12 to 140 km from the epicenter, with the closest stations near the Cerro Prieto geothermal power plant. These stations were deployed over sediments (six in total). Additionally, we analyzed records of six more stations deployed over rock, with the farthest station near Ensenada city (Figure 2).

The recording instruments used are Kinometrics Etna (Pasadena, CA, USA) or GeoSIG GMS-18 (Schlieren, Switzerland). They recorded ground accelerations. All stations record three components of the ground motion and operate with a sampling rate of 200 m/s. Table 1 shows the site description and recording instrument of each station, and Figure 3 shows the location of each one.

Table 1. Characteristics of the stations (the whole stations in this table record ground accelerations)

Station	Latitude	Longitude	Height (nmm)	Site Type	Accelerometer
Geothermal plant (GEO)	32.400	−115.240	30	Sediments	Etna, Kinematics
Saltillo (SAL)	32.422	−115.130	50	Sediments	GeoSIC GMS-18
M. De Ocampo (MDO)	32.464	−115.316	14	Sediments	GeoSIC GMS-18
Chihuahua (CHI)	32.488	−115.242	15	Sediments	GeoSIC GMS-18
Tamaulipas (TAM)	32.549	−115.235	15	Sediments	GeoSIC GMS-18
RIITO (Rii)	32.165	−114.961	15	Sediments	GeoSIC GMS-18
Rancho San Luis (RSL)	32.116	−115.840	1490	Solid Rock	GeoSIC GMS-18
Heroes of the Ind. (HDI)	32.615	−115.882	1130	Solid Rock	Etna, Kinematics
Rancho Agua Caliente (RAC)	32.020	−116.301	714	Solid Rock	GeoSIC GMS-18
Trinity Valley (VTR)	31.398	−115.714	750	Solid Rock	Etna, Kinematics
Three Brothers (TRH)	31.690	−116.190	800	Solid Rock	GeoSIC GMS-18
CICESE (CIC)	31.868	−116.664	60	Solid Rock	GeoSIC GMS-18

**Figure 3.** The stations' locations are included in Table 1.

Seismic energy propagates through the earth and dissipates according to attenuation laws that depend on the distance and type of material it travels through. Hard material facilitates propagation, while soft material makes the propagation more difficult and dissipates seismic energy faster. To show this effect, we picked the maximum acceleration of the horizontal components at each station and plotted them versus the distance from the epicenter (Figure 4).

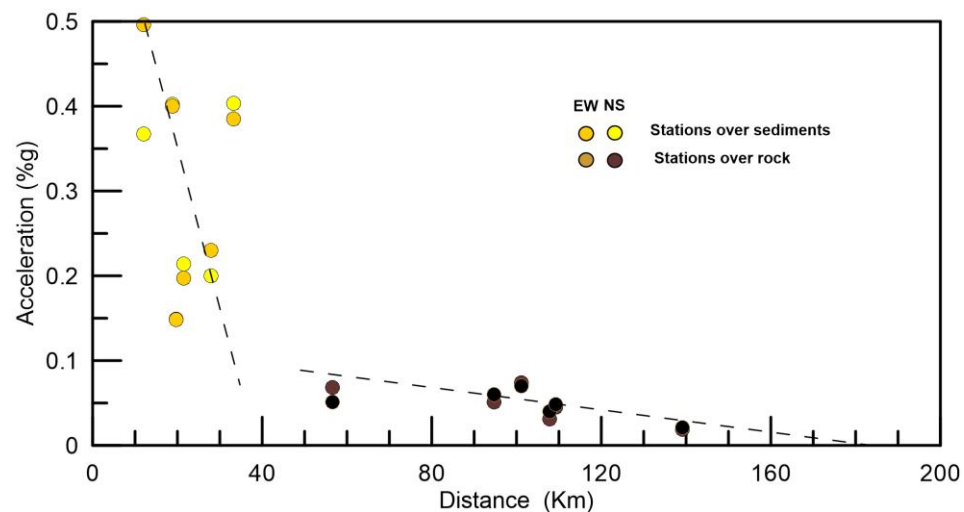


Figure 4. Attenuation of peak acceleration with distance at seismic stations used for both rock and sediment stations. Dashed lines are plotted only to reflect the decay tendency of each group of stations.

The acceleration response of the sediments compared to that of the rock can be observed (Figure 4). It is worth saying that the closest stations are within a sedimentary valley. In contrast, the other stations are located within the peninsular ranges' batholith. The highest acceleration recorded was 0.496 g. It was picked from the EW component of the GEO station located 12 km from the epicenter (station settled over sediments), while the highest acceleration recorded over the rock was 0.074 g at the RAC station located 101 km away.

The NEHRP (National Earthquake Hazards Reduction Program) researched seismic accelerations by considering a probabilistic criterion and a return period of 475 years. According to the results, rock acceleration values between 0.36 g and 0.46 g were determined for the area. The values recorded at rock stations are an order of magnitude below that range, while the values observed at sediment stations are higher but close to it.

2.3. Site Effect

Frequently, site effects have an important influence on the damage distribution during large earthquakes. Subsoil impedance contrasts can substantially amplify the shaking level and increase the duration of strong ground motion. As the city is over-sedimentary and has very homogenous soil, we explore a hypothetical response of the entire valley.

One way to estimate the site effect of an area is by modeling the seismic response of soil deposits. Using their stratigraphic characteristics and the mechanical and dynamic properties of the materials that compose them, we can estimate the transfer function that represents the medium's response to an earthquake. Ground motion modeling can be obtained through a theoretical propagation of a green function through this layered media.

The physical characterization of the soil is obtained from soil mechanics studies. Data from a geotechnical study conducted in the city of Mexicali were used. The propagation velocities of the shear waves (V_s) of the different strata were estimated using expressions that allow us to determine V_s using only the number of hits obtained from standard soil penetration tests. Two of them [27,28] were compared for this study (Figure 5).

$$V_s = 80.6 \times N^{0.331} \quad (1)$$

$$V_s = 88.4 \times N^{0.333} \quad (2)$$

where N is the number of hits in the standard penetration test.

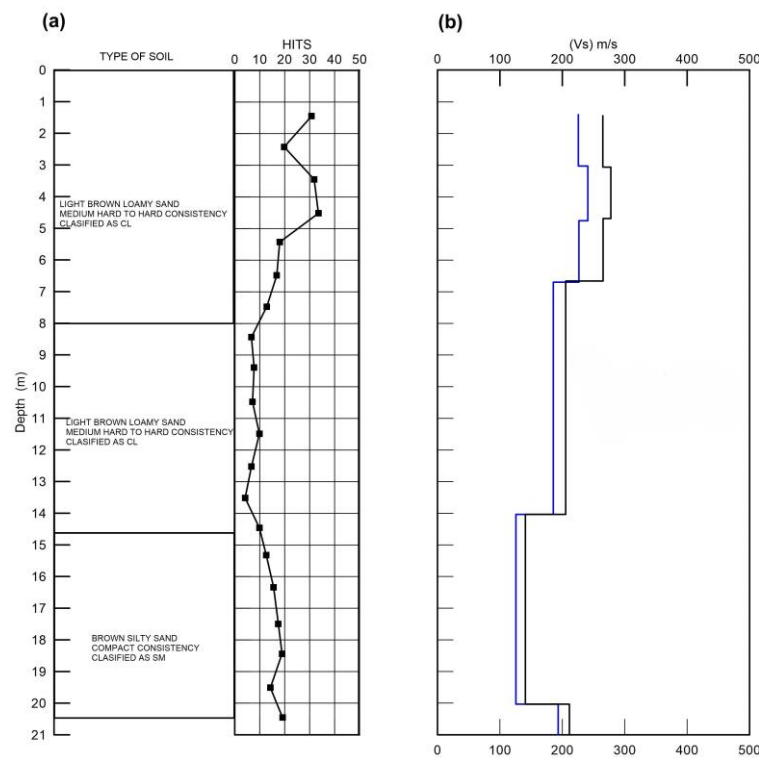


Figure 5. (a) Stratigraphic profile obtained from the geotechnical survey; (b) variation of the shear wave (V_s) with depth using the expression of Imai of 1977 (blue line) [26] and the expression of Ohta & Goto in 1978 (black line) [27].

Velocities obtained from both expressions give similar results, so our velocity profile was the average of both. A 6-layer model with variable thicknesses and shear wave velocities ranging from 90 to 180 m/s and a semi-space assigned a shear wave velocity (V_s) of 400 m/s. Low-velocity layers can be seen from about seven to twenty meters. We recognize that a single geotechnical survey conducted at one site is insufficient to represent a geographic region, but given the very homogeneous physical characteristics of the soil in the Mexicali Valley, we consider the sampled site to be a reasonable sample of regional soils.

The average shear wave velocity, as well as the dominant period of the site, were estimated using the following expressions:

$$V_s = \frac{\sum_{i=1}^n h_i}{\sum_{i=1}^n \left(\frac{h_i}{V_{s_i}} \right)} \quad (3)$$

$$T_s = \frac{4h}{V_s} \quad (4)$$

where h_i and V_{s_i} are the thickness and shear wave velocity at each layer of the stratigraphic profile. The estimated average velocity up to 30 m depth was 155.84 m/s (V_{s30}). According to the NERPH code, this value would correspond to a type E soil (intermediate to soft consistency). The estimated site period was $T_s = 0.77$ s, typical of soils with an intermediate to soft consistency.

In addition to this result, three measurements of ambient seismic noise were made at the same site where the geotechnical study was carried out. Spectral ratios of horizontal components relative to the vertical recorded simultaneously were calculated to obtain the dominant period or natural frequency of vibration of the site using the Nakamura, 1989, technique [29]. We obtained three ambient vibration records with durations of three minutes each. In every record, we selected a window that showed the fewest transient signals, and the noise appeared more stationary. We calculate the spectral relationship

between horizontal and vertical movement from the selected window. These relationships produced HVSR graphs where a peak could be identified from which a dominant period value was determined (Figure 6). Impedance contrasts between soft the soil layer and its basement can significantly amplify the shaking level and increase the duration of strong ground motion. It is reflected in the resonant frequency of the site, and the HVSR technique provides a reliable estimate of this resonant frequency.

The open-source Geopsy (Geophysical Signal Database for Noise Array Processing) software 3.3.3 [30] was used for this analysis.

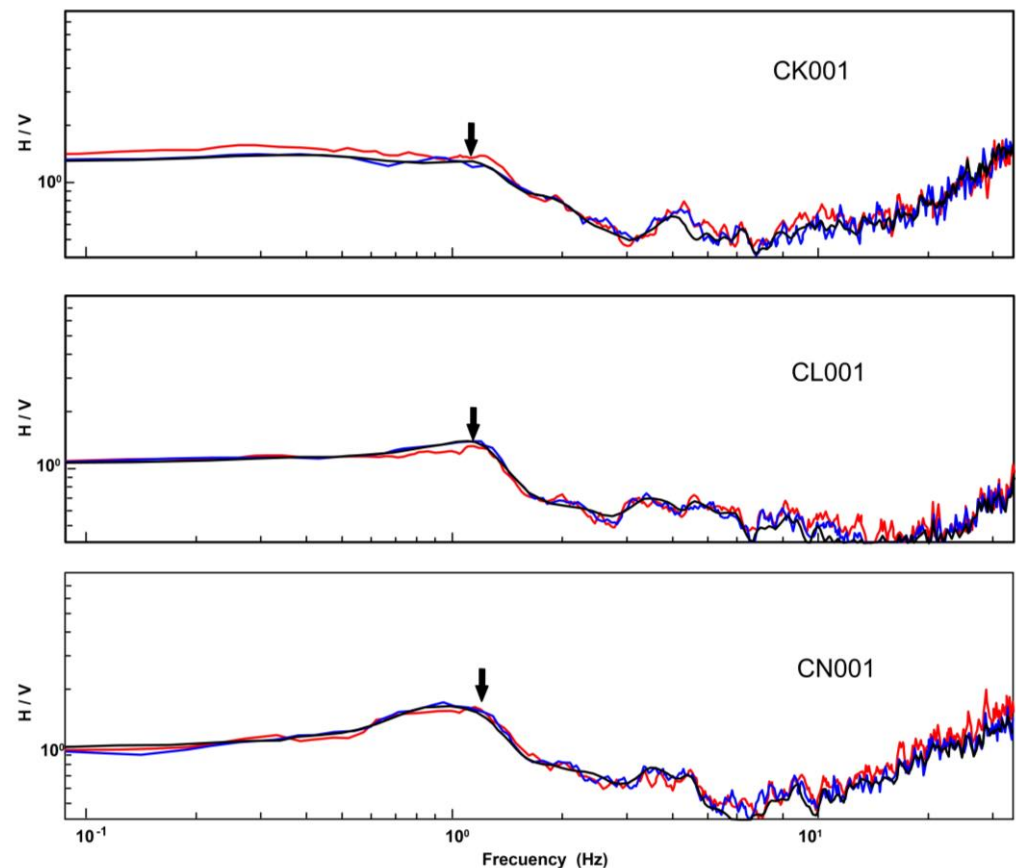


Figure 6. Spectral ratios from seismic noise measurements at three points at the same site where the geotechnical survey was conducted. Three measurements (red, blue, and black lines) were taken at each point. The arrow indicates the position of the dominant period.

The average value obtained was 1.155 Hz or 0.865 s, as determined by Equation (4).

2.4. Transfer Function

For modeling purposes, the seismic record observed at the surface can be viewed mathematically as the result of the convolution of the function describing the seismic energy propagating through the earth's interior and the function describing the response of the soil structure.

One of the most widely used methodologies to obtain it is through the propagation matrix or the so-called Thomson–Haskell method (proposed by Thomson [31] and corrected by Haskell [32]). The method describes the transformation H that an input signal $e(t)$ undergoes as it travels through a medium and generates an output signal $s(t)$, which is the movement of the ground at the surface. The medium is modeled by a set of homogeneous layers superimposed on each other (vertically heterogeneous, isotropic, and elastic medium), and the properties that define the medium do not vary continuously but discretely. The method works by assuming a linear behavior of the soil. Under these

conditions, the equations of motion and the constitutive relations can be combined so that only the first-order derivatives of the stress and displacement concerning the depth ordinate (z) are needed to describe the motion according to Equation (5).

$$\frac{d}{dz}f(z) = A(z)f(z) \quad (5)$$

where $f(z)$ is a vector containing the relation of stresses and strains to depth, and $A(z)$ is a matrix $n \times n$ (in the case of SH waves $n = 2$), which depends on the elastic parameters of the medium according to:

$$A(Z) = \begin{pmatrix} 0 & \mu^{-1} \\ \mu\omega p^2 - \rho\omega^2 & 0 \end{pmatrix} \quad (6)$$

Since the method works with homogeneous layers, the elastic parameters do not vary within a layer, so it does not depend on the z -depth within each layer. Once the matrix incorporates the dynamic properties from the base of the deposit to the point where the elastic response of the deposit is to be known, a propagation method can be applied [33], described by (7) and (8).

$$f(z) = (Z, Z_0)f(Z_0) \quad (7)$$

$$P(Z, Z_0) = e^{(Z, Z_0)A} \quad (8)$$

We used the Degtra software 9.3 [34] to obtain the transfer function (Figure 7) of the stratigraphic profile described in the previous section. Density and damping were chosen according to the material found in the geotechnical study (Figure 5).

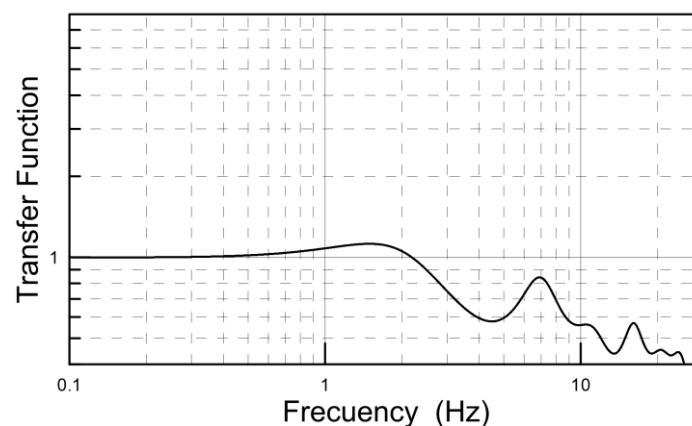


Figure 7. The transfer function was calculated for the incidence of vertical flat shear waves in the profile of Figure 4.

Comparing this function with the spectral quotients estimated from seismic noise, it can be seen that the results are similar up to 5 Hz. We consider that spectral ratios can be considered as empirical transfer functions up to this frequency.

Once the transfer function is obtained, a synthetic seismic record can be generated using any input signal (Green's function) and a numerical simulation of propagation through the medium (convolution). This record will represent the movement at the surface due to the site effect. One goal of calculating transfer functions is to use them to estimate the response of a site due to the occurrence of an earthquake where seismic records are not available.

As Green functions, we chose the horizontal acceleration records of the nearer stations to the April 2010 event.

Since these stations are on sediments and therefore are affected by the site, we first had to remove this effect. As we do not have a stratigraphic profile for these sites, we used empirical transfer functions obtained by spectral quotient [29], as we did for the site in

Mexicali, and applied a deconvolution process with the corresponding record. The stations considered for this analysis were CHI, TAM, SAL, GEO, MDO, and RII, the closer stations to the epicenter. The transfer functions obtained are shown in Figure 8.

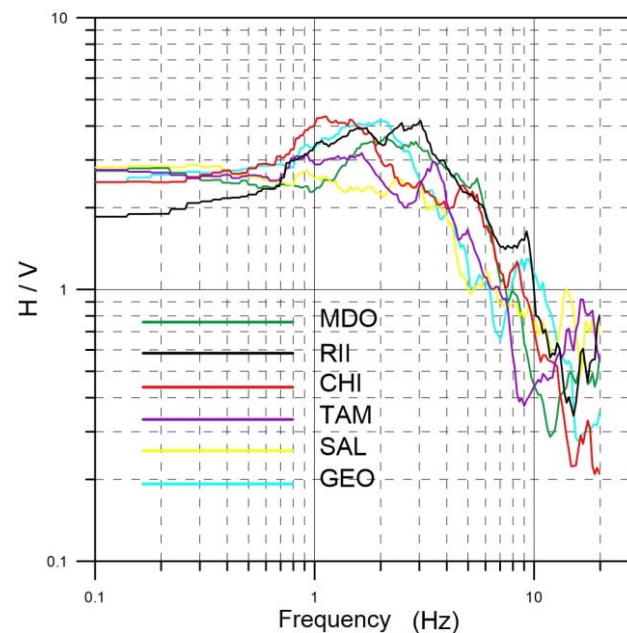


Figure 8. The empirical transfer functions were obtained for stations close to the epicenter of the 4 April 2010 earthquake.

The objective of the process is to calculate response spectra for Mexicali from the synthetic records obtained using the technique described in the previous paragraph and compare them with the regulations established in the MOC-CFE [18], which is the one currently used in the city.

2.5. Response Spectra

Response spectrum is a valuable tool to support, in some cases, the seismic design of structures (buildings, bridges, etc.). It represents the maximum response of a structure considered as a system of one degree of freedom to different periods of vibration due to the features of ground motion triggered by an earthquake.

From a ground acceleration record, the displacement, velocity, or acceleration response of a system with one degree of freedom can be calculated for a defined damping value and for different values of natural vibration periods as a function of time. The response spectrum is calculated by taking the maximum response values considering the absolute maximums, of each analysis for different natural periods of vibration. The results are charted as a function of the periods of vibration.

In recent years, significant efforts have been made to clearly describe the procedure for determining a design spectrum based on response spectra and other considerations. The design spectrum usually has a smoother shape than the response spectrum. One purpose of these efforts is that the structural engineer can properly use the response spectrum and the design spectrum to understand the probable behavior of the building that he is designing.

Generally, design regulations [15–18] propose a series of design spectra that are obtained by considering aspects of regional tectonics, seismology, seismic hazard, and, in a few cases, site-specific considerations.

This last fact makes it necessary for the spectra proposed by the building regulations to be reviewed and compared with those obtained considering the aforementioned aspects in addition to the properties of the site of interest. This last procedure allows for the

verification of whether site-specific data were considered for the determination of the design spectrum.

To have criteria for making decisions associated with seismic actions in building design, it is advisable to have basic information about seismic hazard assessment. Particularly, to define the seismic actions, the design spectra are an essential tool that is frequently used in building regulations. If these design spectra are obtained from a number of response spectra related to a complete catalog of earthquakes, then the maximum response can be reasonably estimated for a specific site. However, there is not enough information in several regions of Mexico.

Soil seismic response in MOC-CFE [18] can be determined using the software called PRODISIS v4.1 [35], where estimation of site effect is mainly tied to T_s and to shear-wave velocity. The stratigraphic profile can be replaced by a single layer with a velocity equal to the mean velocity of the actual profile. Non-linearity is considered by means of a factor called non-linearity factor, which depends, among other parameters, on T_s , mechanical impedance contrast, and a so-called distance factor.

Using the signals obtained at the surface, i.e., already affected by the site effect given in Figure 6, the response spectra with 5% damping were obtained for the site and compared with the design spectrum proposed by MOC-CFE [18]. Figure 9 shows this comparison. The smoothed spectrum (orange) corresponds to that proposed by the regulation.

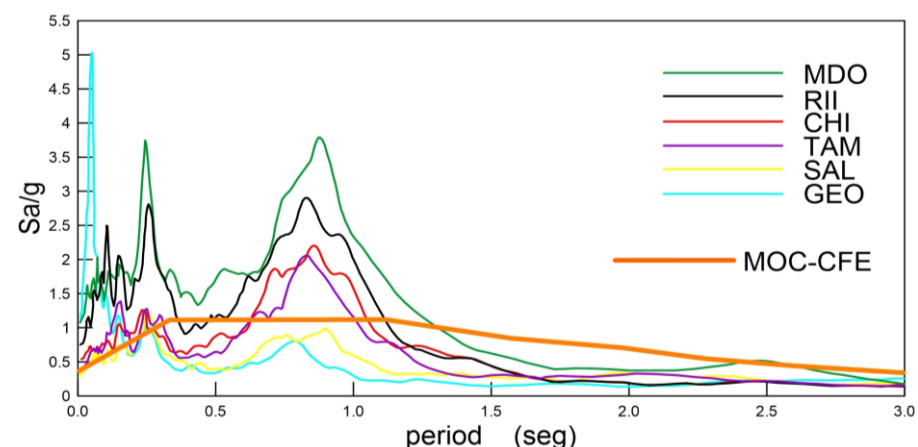


Figure 9. The 5% response spectra (colored lines) for each recording station and design spectrum (MOC-CFE).

It can be seen in Figure 9 that in all cases, there are pulses, and almost all of them are more significant than the design spectrum proposed by MOC-CFE [18]. The shape of these pulses can be attributed to a near-fault ground motion as suggested by some authors [36,37], as the records used are from stations close to the epicenter, but multi-pulse or single pulse (the closest station, GEO, shows the greater amplitude in a single pulse at 0.05 s), amplitudes are greater than the MOC-CFE design spectra.

Figure 8 comparison suggests that the amplitudes are well predicted by design spectra for periods higher than 1.3 s, but it is highly probable that MOC-CFE [18] underestimates amplitudes for periods lower than 1.3 s. The spectrum of the CFE regulation can be considered as a representative spectrum for Mexicali for periods greater than 1.3 s, but not for the zone of short periods.

3. Conclusions and Recommendations

A spectral analysis was carried out using the seismic records of April 2010, $M_w = 7.2$, obtained in the region of Mexicali, B.C. Records from the nearest stations to the epicenter were considered for this study. In addition, information from a geotechnical profile obtained in the urban center of the city of Mexicali, B.C., was used. Due to the uniformity of the existing soil in this city, such geotechnical information can be considered

representative of the area under study. With the main idea of reviewing the design spectrum currently used in the region [18], an equivalent linear method was used to propagate the site-corrected SH waves through the aforementioned geotechnical profile. Using the synthetic records obtained for the surface, the elastic response spectra at 5% damping were calculated for each station and compared with the local design spectrum [18].

Based on our analysis, we suggest that the design spectrum of the CFE regulation can be considered a representative spectrum for the city of Mexicali for periods greater than 1.3 s (flexible structures) but probably not for short periods. The current design spectrum can be considered non-conservative for structures with vibration periods of 0.3 to 1.3 s.

The design of new structures with a natural vibration period within this window must consider that the amplitudes established in the CFE regulation are not the maximum amplitudes that can occur. The design spectra have a smoother shape because they are obtained by considering aspects of regional tectonics, seismology, and seismic hazard rather than site-specific considerations.

In this sense, it is essential to emphasize that the results obtained in this study were obtained from real data for this specific site.

More site effect studies are needed in Mexicali. Dynamic amplification functions and soil mechanic studies should be performed all over the city to create a proper database, which is essential for any reliable building regulations.

It is advisable to continuously update the MOC-CFE [18] with local data and contribute to increasing data collection, but more importantly, to creating official building regulations for the country's main cities.

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