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Original paper

# Seismic characterization of station LNIG as a reference site in Northeast Mexico

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**Resumen**

La estación LNIG forma parte de la nueva generación de observatorios sismológicos que han sido instalados en los últimos años en la República Mexicana por el Servicio Sismológico Nacional (México). La estación LNIG se instaló en enero de 2006 en terrenos de la Facultad de Ciencias de la Tierra de la Universidad Autónoma de Nuevo León en Linares, Nuevo León, México. Evaluamos la respuesta de sitio de la estación LNIG de acuerdo con la definición del sitio estándar de referencia. Se obtuvo (a) el valor promedio de velocidades de ondas de corte para los primeros 30 m del subsuelo, $V_{S30}$, y (b) la frecuencia de resonancia. A partir de perfiles de refracción sísmica, obtuvimos $V_{S30}$ = 1870 m/s. De acuerdo con la NEHRP, corresponde a un sitio clase A (roca dura o macizo rocoso). La frecuencia de resonancia fue obtenida mediante cocientes espectrales *H*/*V* de registros de microtremores y de sismos locales (3.1 ≤ *M* ≤ 4.5), los cuales muestran una respuesta plana con amplitud unitaria, para el rango de frecuencias de 0.2 a 20 Hz. De acuerdo con la definición propuesta por Steidl *et al*. (1996) y Cadet et al. (2010), la estación sismológica LNIG queda definida como un sitio de referencia, el cual se encuentra asentado sobre lutita de la Formación Méndez del Cretácico superior.

Palabras clave: sitio sísmico de referencia, terremotos intraplaca, microtremores, sismos locales de baja magnitud, cocientes espectrales *H*/*V*, $V_{S30}$, Sierra Madre Oriental.

**Abstract**

Station LNIG is part of the new generation of seismological observatories that have been recently installed in Mexico by the Servicio Sismológico Nacional (Mexico). This station started operations in January 2006 in the Facultad de Ciencias de la Tierra from the Universidad Autónoma de Nuevo León, in Linares, Nuevo León, Mexico. We evaluate the site response at LNIG according to the definition of standard reference rock site. We obtained (a) the average shear wave velocity for the first 30 m depth, $V_{S30}$, and (b) the resonance frequency. We got $V_{S30}$ = 1870 m/s from seismic refraction profiles. This corresponds to a hard rock site type A in accordance to NEHRP. On the other hand, the spectral ratios were obtained from microtremors and local weak-motion earthquakes (3.1 ≤ *M* ≤ 4.5), they show a flat response (unitary amplitude) for the frequency range from 0.2 to 20 Hz. According to the definition proposed by Steidl *et al*. (1996) and Cadet et al. (2010), the LNIG site, located on shale of the Mendez Formation of the Upper Cretaceous, corresponds to a reference site.

Key words: seismic reference site, intraplate earthquakes, microtremores, weak motion earthquakes, *H*/*V* spectral ratios, $V_{S30}$, Sierra Madre Oriental.

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## Introduction

It is known that seismic site amplification is responsible for great damage in several cities located around the world. This seismic amplification is the outcome of high contrast of seismic impedance between two media, which produces important modifications to the seismic input signals that arrive to the surface. To quantify how the input motion is modified by the shallow surface geology and the subsoil geometry, it is necessary to know a reference for the site amplification. Such reference is defined as seismic reference site, which has been related to a bedrock outcrop. The recording at the reference represents the signal at the base of the column (without the free surface effect) (Steidl *et al*., 1996; Cadet *et al*., 2010). To evaluate site effects and to test if the site is a reference site, several methodologies have been suggested: the first one is proposed by Borcherdt (1970), who suggests the use of the traditional standard spectral ratio method to quantify the site effects. This has been mainly implemented in urban areas where a seismic network is located. For example, Singh *et al*. (1988) used a seismic station south of the Mexico City as reference for the motion in this City. Another evaluation of site response focuses on individual stations using horizontal to vertical spectral ratios (*H*/*V*) through weak or strong motion earthquakes records (Lermo and Chávez-García, 1993; Molnar and Cassidy, 2006) and/or through microtremor records (Nakamura, 1989; Lermo and Chávez-García, 1993). The *H*/*V* method uses the vertical component as reference motion (Molnar and Cassidy, 2006). Recently, Cadet *et al*. (2010) defined a standard reference rock site as a site with $V_{S30}$, which is the average shear wave velocity over the top 30 meters of soil, with a velocity between 750 and 850 m/s and with fundamental resonance frequency, $f_0$, higher than 8 Hz.

Station LNIG is one of the latest additions of the Servicio Sismológico Nacional (SSN, National Seismological Service of Mexico), it represents the new generation of seismological observatories that have been recently installed in Mexico (Figure 1) with the main goal of monitoring the seismic activity that occurs in the country. In the expansion process of the SSN, LNIG station has the purpose of covering the local and regional seismicity originated in Northeast Mexico. This station started its operations in January 2006,

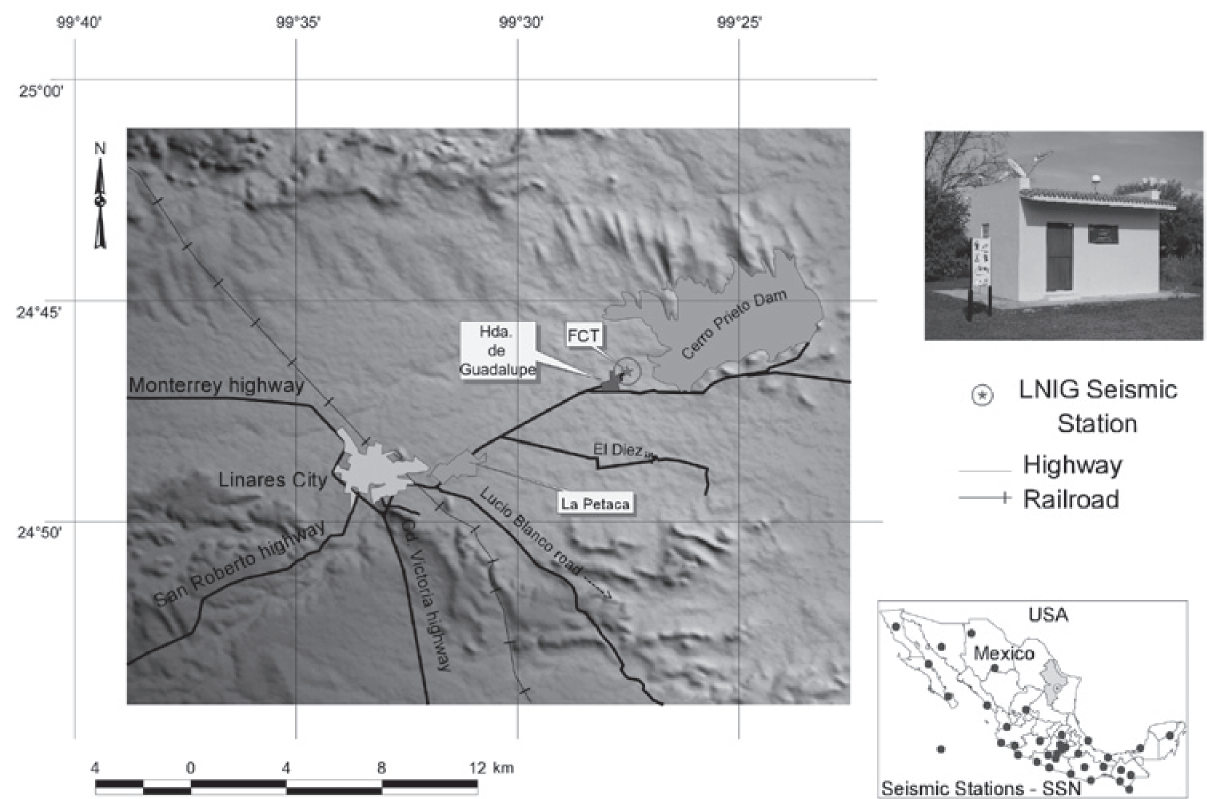


**Figure 1.** Distribution of the seismic stations that are part of the Servicio Sismológico Nacional, and location of LNIG site in Linares, N. L., Mexico.

but it was officially inaugurated on 2 February 2006 (Montalvo Arrieta *et al*., 2006). LNIG station is composed by a triaxial seismometer Streckeisen STS-2 with a flat response to ground velocity in the frequency range from 0.01 to 30 Hz. It also has an accelerometer FBA-23, and a 24-bit Quanterra digitizer. The seismic signals in velocity and acceleration have a sampling rate of 80 samples per second, and are recorded continuously. The data are transmitted in real time by satellite to the central station in Mexico City (SSN in the Instituto de Geofísica, UNAM). Since the station installation and up to date, the noise distribution shows a stable behavior for high frequencies and a broader distribution for long periods, 90% of the distribution is within the new noise level curves defined by Peterson (1993) (Figure 2). In this figure the magenta lines denote de median (continuous) and percentiles 5 and 95 (dashed) of the noise distribution; the Peterson's (1993) reference curves are shown in black.

The aim of this study is to characterize the site response of the LNIG site through its average seismic velocity at 30 m depth ($V_{S30}$), the spectral ratios *H*/*V* from microtremors and local weak motion earthquakes, and correlate our results with the lithological conditions of the subsoil.

## Seismicity

Northeastern Mexico has generally been considered a tectonically stable region, characterized by low seismicity and a lack of strong ground motion records. The absence of seismic networks in northeast Mexico limits the accurate determination of location, magnitude, and focal mechanism of any seismic event in the region. However, recent studies show that seismic activity exists in the area (Casasús, 2003; García-Acosta and Suárez-Reynoso, 1996). Galván-Ramirez and Montalvo-Arrieta (2008) summarize the regional seismicity from 1787 to 2006 in a catalog of 144 earthquakes with magnitudes ranging between 2.3 and 4.8, and four major earthquakes: Bavispe, Sonora, 1887 ($M_W$ = 7.4, Natali and Sbar, 1982), Parral, Chihuahua, 1928 ($M_W$ = 6.5, Doser and Rodriguez, 1993), Valentine, Texas, 1931 ($M_W$ = 6.4, Doser, 1987) and Alpine Texas in 1995 ($M_W$ = 5.7, Xie, 1998; Global Centroid Moment Tensor Catalog; Frohlich and Davis, 1987).

Since its installation, station LNIG has recorded sixteen local earthquakes (3.1 ≤ $M_L$ ≤ 4.5; Table 1). The SSN reported a $M_W$ of 5.0 and 5.1 for the events of 14 June 2009 (4 and 5, in Table 1). Figure 3 shows the epicentral location of these earthquakes and the historic seismicity reported by Galván-Ramírez and Montalvo-Arrieta (2008) for a northeast sector of Mexico. In this same figure, the strong ground motion records of the N-S component are shown, together with the two focal mechanisms, obtained by the SSN, for the events of 17 April 2006 ($M_W$ = 3.3) and 14 June 2009 ($M_W$ = 5.1).

The events (4 and 5, in Table 1) of 14 June 2009 were felt in Allende, General Terán and Montemorelos; in the last two cities the ground shake was severe according to newspaper reports. The 15 June 2010 earthquake (*M* = 3.4) was located 4 km west of Montemorelos city. This event was felt in Allende, General Terán and Montemorelos cities. In Montemorelos town, power outages and minor damages in some schools were reported. Previously on 6 April 2004, an earthquake (*M* = 3.9) occurred near Montemorelos city. This small earthquake was felt in two small towns (Montemorelos and General Terán, within 20 km radius) in the Gulf Coastal Plain region, between Monterrey and Linares (Figure 3). Some damage to houses was reported in Montemorelos.

The earthquakes of 20 and 21 June 2009 (*M* = 3.5, 3.7 y 3.7; SSN; Figure 3) were felt in some localities of the Galeana municipality, N. L. The epicentral area of the 20 June 2009 events was in San José de la Joya (Figure 3). The damage to houses and the elementary school in this place was reported as cracks, broken and

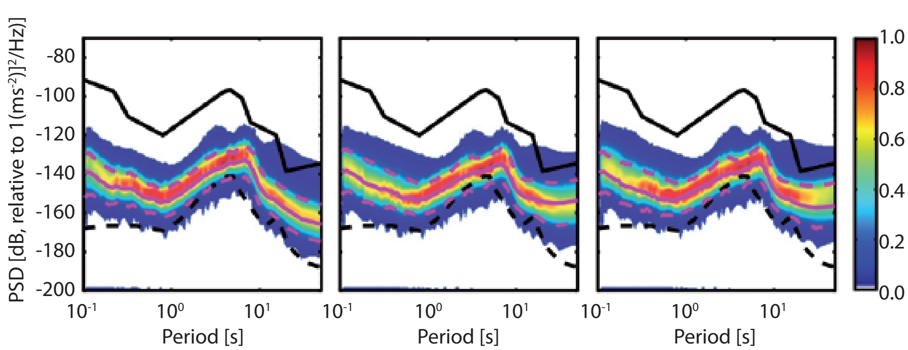


**Figure 2.** Normalized noise distribution for the three components (left = vertical, center = north, right = east). Peterson's (1993) reference curves are shown in black (NLNL = dashed, NHNL = continuous). The magenta lines denote de median (continuous) and percentiles 5 and 95 (dashed) of the distribution.

**Table 1.** Recent local (2006-2010) earthquakes recorded in LNIG, the location is given by the SSN.

| Event | Date (dd-mm-aaaa) | Local Time | Latitude (ºN) | Longitude (ºW) | Depth (km) | Local Magnitude |
|---|---|---|---|---|---|---|
| 1 | 17-04-2006 | 11:25:10 | 25.32 | 100.38 | 20 | 4.3 |
| 2 | 17-04-2006 | 11:58:04 | 25.23 | 100.29 | 20 | 4.1 ($M_w$ 3.3) |
| 3 | 05-06-2006 | 08:48:13 | 24.80 | 99.23 | - | 3.1 |
| 4 | 14-06-2009 | 06:04:03 | 25.5 | 99.31 | 10 | 4.5 ($M_w$ 5.1) |
| 5 | 14-06-2009 | 06:04:06 | 25.3 | 99.33 | 20 | 4.4 ($M_w$ 5.0) |
| 6 | 20-06-2009 | 03:56:16 | 24.89 | 100.26 | 20 | 3.5 |
| 7 | 20-06-2009 | 03:57:50 | 24.87 | 100.26 | 20 | 3.7 |
| 8 | 21-06-2009 | 21:08:06 | 24.86 | 100.22 | 20 | 3.7 |
| 9 | 20-01-2010 | 15:56:28 | 25.62 | 100.40 | 5 | 4.0 |
| 10 | 13-02-2010 | 17:52:30 | 25.72 | 101.03 | 20 | 3.8 |
| 11 | 26-05-2010 | 03:11:47 | 24.63 | 100.30 | 3 | 3.9 |
| 12 | 15-06-2010 | 11:28:41 | 25.18 | 99.87 | 5 | 3.4 |
| 13 | 30-08-2010 | 05:43:00 | 25.15 | 99.09 | 20 | 3.5 |
| 14 | 08-09-2010 | 12:46:05 | 23.97 | 99.39 | 28 | 3.6 |
| 15 | 03-10-2010 | 22:16:36 | 25.24 | 99.23 | 20 | 3.6 |
| 16 | 05-10-2010 | 03:24:45 | 25.38 | 101.35 | 5 | 3.7 |

deformed windows. All the structures in the area are made of masonry. The damage observed is correlated with seismic intensities of IV-V (Montalvo-Arrieta, 2009). Before this events, another earthquake was felt in the area in 26 February 1986 ($M$ = 4.4). There are also reports of a strong earthquake on 28 April 1841 that caused damage to the church of Galeana city (Leal Ríos, 2001).

An earthquake of $M$ = 4.0 (SSN, Figure 3) occurred on 20 January 2010, it was located 11 km southwest of Monterrey and 5 km south of San Pedro Garza García. This event was slightly felt; however, no damage was reported in the Monterrey Metropolitan Area (MMA). The MMA is located at the frontal part of the SMO, north of the Monterrey salient (Padilla and Sanchez, 1982; 1985). There have been at least eight earthquakes in this area with a magnitude range from 3.6 to 4.6 in the 1982 – 2010 period (Figure 3; Galván-Ramírez and Montalvo-Arrieta, 2008; SSN). In addition, there is evidence of ancient earthquakes felt in the MMA (García-Acosta and Suárez-Reynoso, 1996). Casasús (2003) mentioned that on 28 Abril 1841, strong shaking was felt but it was of short duration. This quake is the same that caused damage in Galeana City. Also, the USGS National Hazard Maps (Frankel *et al*., 2002) shows values of 12–16 PGA (%g with 2% probability of exceedance in 50 years) in this area.

## Location and geological setting

The LNIG station is located at the Facultad de Ciencias de la Tierra, Universidad Autónoma de Nuevo León (FCT-UANL), in Linares, N. L., Mexico (Figure 1) in a wide transition zone between the SMO fold-thrust belt and the Gulf Coastal Plain (GCP) in Northeast Mexico. The SMO is mainly a sequence of carbonate and clastic marine sedimentary rocks of Late Jurassic and Cretaceous ages, complexly folded and overthrusted during the Laramide Orogeny (Padilla and Sánchez, 1982; 1985; Eguiluz de Antuñano et al., 2000). The GCP corresponds to a thick sequence of clastic sediments from Tertiary age characterized by an extensional deformation (Echánove, 1986; Ortíz-Ubilla and Tolson, 2004).

In the Linares area, the oldest outcrops correspond to the Mendez Formation. This Formation is composed of shale of upper Cretaceous age, which has a thickness greater than 45 m and it is defined as bedrock (Montalvo-Arrieta *et al*., 2005; Infante *et al*., 2010). Younger rocks include conglomerates (Tertiary age), Quaternary alluvium and recent soils, mostly silts. The maximum thickness of these Quaternary deposits occurs in old stream beds which are mainly oriented in east–west direction (Montalvo-Arrieta *et al*., 2005). Montalvo-Arrieta *et al*. (2005) identified four different lithological units that outcrop in the Linares area with the following average $S$ waves velocities: silts with

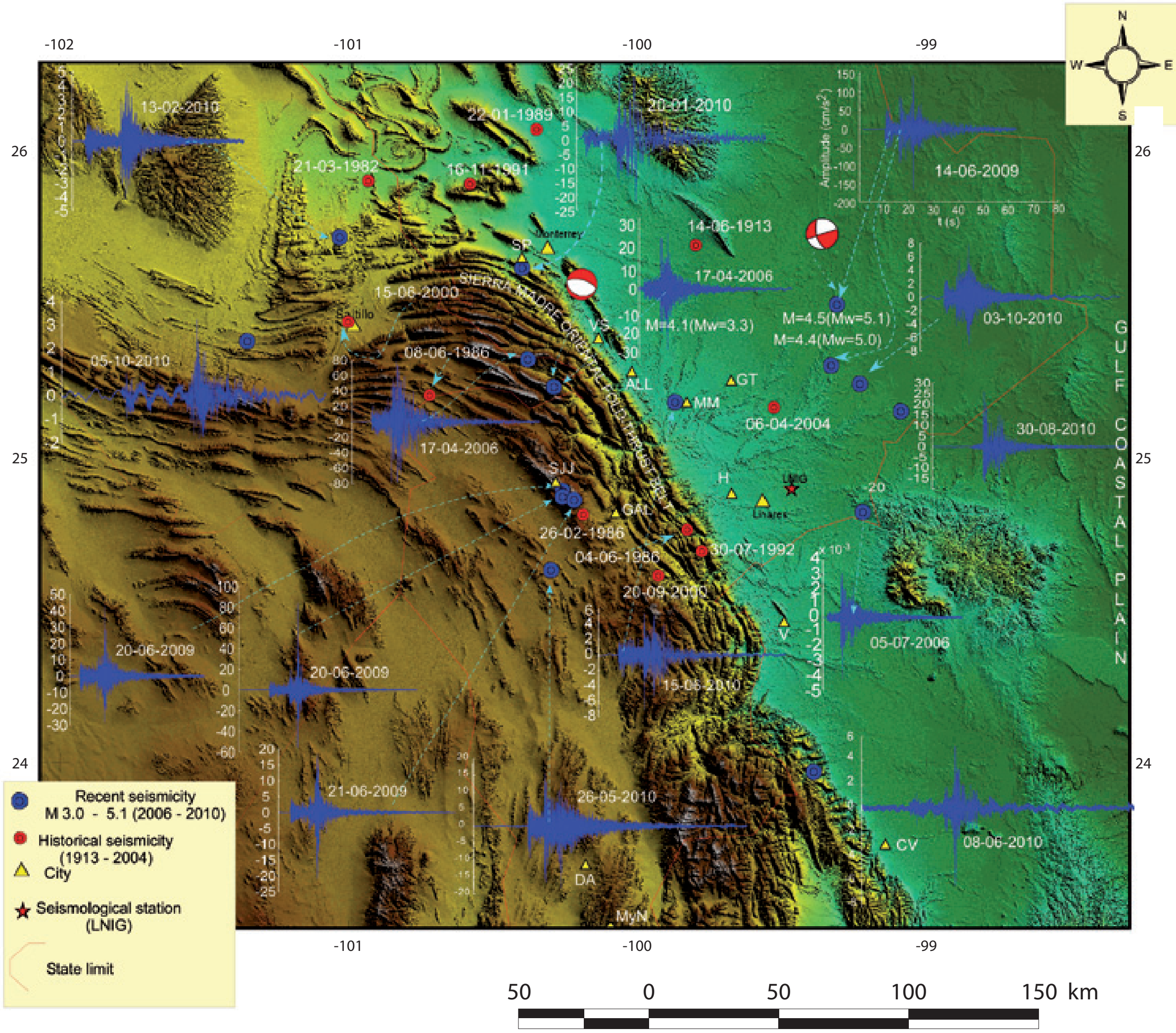


**Figure 3.** Epicentral location of historic (red dots; Galván-Ramírez and Montalvo-Arrieta, 2008) and recent (blue dots) earthquakes recorded in LNIG station (red star). The time series of acceleration corresponds to the north – south component. The focal mechanism corresponds to the RCMT obtained by the SSN. Triangles represent cities and localities in northeast Mexico (Saltillo; Monterrey; SP: San Pedro Garza García; VS: Villa de Santiago; ALL: Allende; MM: Montemorelos; GT: General Terán; H: Hualahuises; Linares; GAL: Galeana; SJJ: San José de la Joya; V: Villagrán; CV: Ciudad Victoria; DA: Dr. Arroyo; MyN: Mier y Noriega).

221 m/s, alluvial deposits with 559 m/s, Tertiary conglomerates with 1,220 m/s and shale of the upper Cretaceous Mendez Formation with 2,149 m/s. At the FCT-UANL area, in a nearby site of the LNIG station (Figure 4), Infante *et al*. (2010), correlating electrical resistivity and seismic velocity values and using crossgradient joint inversion with geotechnical information, found that the shallow subsoil is composed by two layers: the first defined as alluvial deposits (silts, sandy clays, caliche nodules and gravels) with thickness less than 4 m and *P* waves velocities that vary from 400 to 750 m/s. The second one overlying bedrock is composed by Mendez Formation shale with *P* waves velocities ranging from 800 m/s to more than 1,200 m/s for depths that vary from 4 to 10 m. In the FCT-UANL area, the Mendez Formation is composed of shale slabs, gray shale and marls. The LNIG site is placed on the Mendez Formation.

**Seismic velocity structure and definition of rock site**

In accordance with the National Earthquake Hazards Reduction Program (NEHRP) and the study of Borcherdt (1994), the average shear wave velocity of the first 30 m ($V_{S30}$) of subsoil is used to classify sites for building codes in several cities in the world. When $V_{S30}$ > 1500 m/s (site class A according NEHRP) the site is considered as hard rock site.


**Figure 4.** Seismic refraction profile location (white continuous line) used to determine the seismic velocity structure ($V_{S30}$) at LNIG station. The location of the seismic refraction profiles (red dashed line) by Infante *et al*. (2010), is also shown.

The seismic velocity structure in the upper 30 m at the LNIG site was measured by seismic refraction profiles. The seismic data was interpreted using travel-time curves. First-arrival phases were picked assuming they were refracted in the same interface. Velocities were computed from the slope of the line connecting arrivals, assuming that the velocity is constant along the profile. We used a RAS-24 Remote Acquisition System with 24-bit A/D conversion in a 24-channel box, with horizontal and vertical geophones and a sledgehammer as seismic source. The seismic line covers a total length of 66 m. We carried out four seismic refraction direct and reverse profiles for both *P* and *S* waves. The shot points were located at positions -3 m, -6 m, and -9 m, over each extreme of the line and the separation between geophones was 3.0 m.

From the data analyzed and velocities obtained according to the travel-time curves along the profile, two layers were indentified in the subsoil. The first one was identified as the weathered part of the Mendez Formation with an average thickness of 4.5 m and a velocity of 1,630 m/s for *P* waves and 1,100 m/s for *S* waves. The second layer corresponds to the shale of Mendez Formation with velocity of 3,550 m/s for *P* waves and 2,130 m/ for *S* waves. Figure 5 depicts the velocity structure obtained for the LNIG site. The values of the seismic velocities registered for the LNIG site are equal to those observed in the same material at FCT-UANL and Linares area obtained by Infante *et al*. (2010) and Montalvo-Arrieta *et al*. (2005). The $V_{S30}$ value obtained for the LNIG site was 1,870 m/s. Recently, Cadet *et al*. (2010) propose that in terms of seismic velocities, the $V_{S30}$ = 800 m/s value can be considered as a lower limit to the definition of a standard rock site. Therefore, the seismic velocity obtained in the LNIG site corresponds to a rock site. On the other hand, according to the National Earthquake Hazard Reduction Program (NEHRP, 1994; 1997; 2001) and the new European regulations (EC8, Eurocode 8, 2004), the LNIG site is classified as hard rock site with $V_{S30}$ > 1500 m/s (site class A).

**Evaluation of site response using microtremors and weak-motion earthquakes**

In order to evaluate the seismic response of a site, it is necessary to eliminate the source, travel path and instrument response, to preserve the local or soil characteristics below the site of interest. To do this, a spectral ratio of the horizontal components against the vertical component by means of the Fourier spectra amplitude, need to be obtained from recorded earthquakes in the study site. If the place of interest corresponds to that of a bedrock reference site, the site response is assumed to be free from amplification or showing a unitary amplification. We evaluate the seismic site condition at the LNIG site through microtremors and local weak-motion records using the technique of horizontal to vertical spectral ratios, *H*/*V* (Nakamura, 1989; Lermo and Chávez-García, 1993; Molnar and Cassidy, 2006). Several author (i.e. Bonilla *et al*., 1997; Molnar and Cassidy, 2006) mentioned that *H/V* spectral ratios from microtremors provide the fundamental resonance frequency of the site, but fail in determining of the true amplification of the soft soil site. Molnar and Cassidy (2006) noted that amplification of seismic noise ratio can represent the lower-bound of the site effect. In this study the *H/V* spectral ratios from microtremors are used to compare the predominant peak with the spectral ratios of weak motion of the LNIG site.

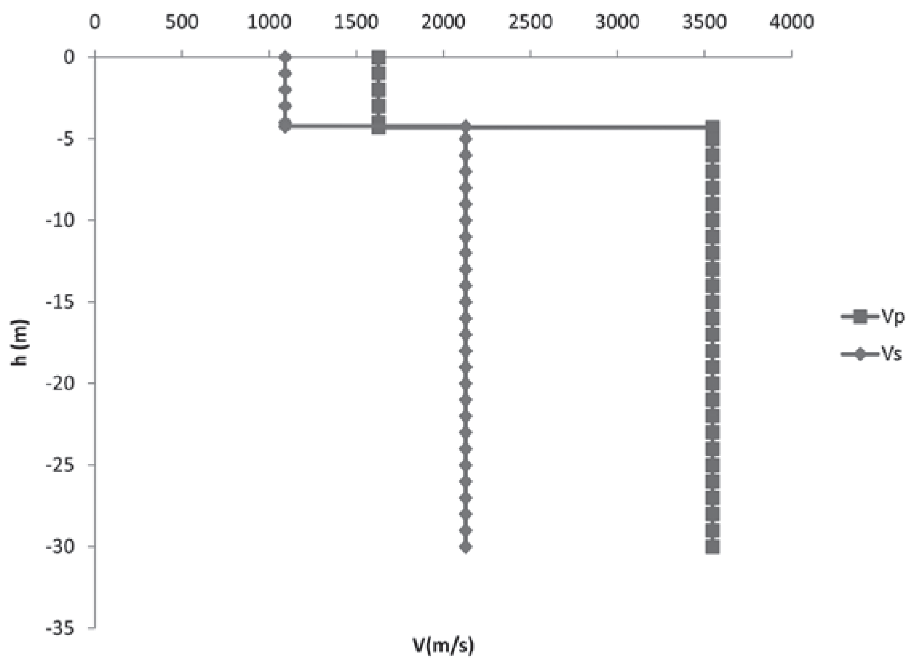


**Figure 5.** Seismic velocity structure of P and S waves obtained in LNIG station from seismic refraction profiles.

*H/V from microtremor records.*

The microtremor records used to obtain the spectral ratios *H*/*V* were selected for the LNIG station using four hours of data recorded in a triaxial seismometer Streckeisen STS-2. They include two hours of daytime and two hours of nighttime. The velocity time series (m/s) were of low amplitude related to natural sources. We selected 60 s time windows, where the time series has minor contribution of high frequencies originated by human activity or by the seismometer, to obtain the spectral ratio. The data processing was the following: (a) removal of trend and offset; (b) band pass filter in a frequency range of 0.005-30 Hz, and a cosine taper with a 5% smooth; (c) computation of the FFT to the selected windows; (d) calculation of the spectral ratio *H*/*V*; (e) estimation of the geometric mean of the spectral ratios, and the standard deviation; (f) finally, the geometric average was smoothed.

Figure 6 depicts the spectral ratios *H*/*V* of the 60 s time windows for the microtremor records in the LNIG station. Figure 6a shows the spectral ratio of the daytime records, and Figure 6b illustrates the same for the nighttime windows. As seen in this figure, the geometric mean of both spectral ratios is flat with amplitude less than 2 in the frequency range of $0.02 \le f \le 5$ Hz; for high frequencies ($f > 6$ Hz) the geometric mean of the spectral ratio falls to value of 1. The results show that the LNIG site corresponds to a rock site without amplification in the frequency band of interest to seismology engineering.

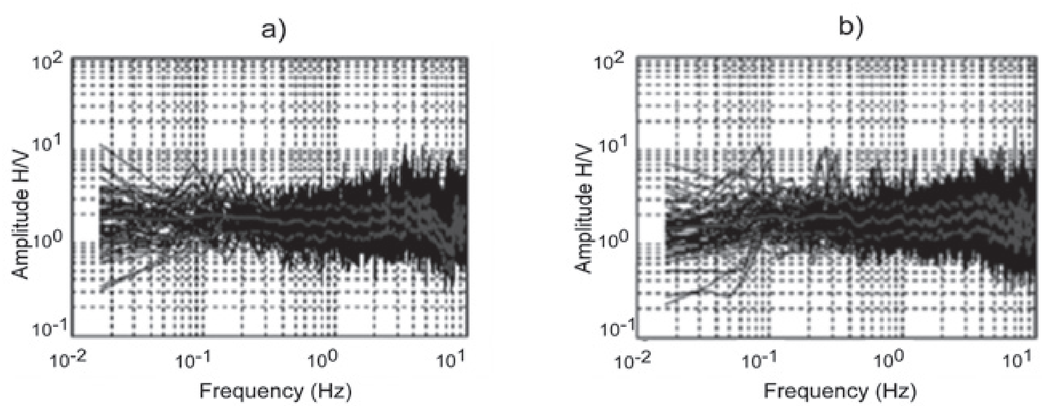


**Figure 6.** Spectral *H/V* ratios for 60 s time windows of microtremors records at LNIG station (black lines). The mean (gray continuous line) and standard deviation are indicated (gray dashed line). (a) Daytime records. (b) Nighttime records.

*Spectral ratios from weak-motion local earthquakes.*

We use the acceleration time series of the sixteen local earthquakes ($3.1 \leq M_L \leq 4.5$; Table 1) recorded in the LNIG station since its installation, to obtain the spectral ratios *H*/*V*. The process is as follows: (a) trend and offset removal; (b) band pass filter in a frequency range of 0.2 - 20 Hz; (c) rotate the horizontal components to obtain the radial and transversal components; (d) compute the FFT for 14 s time window for *S* wave; (d) calculate the spectral ratio *H*/*V* and; (e) estimate the geometric average of the spectral ratios.

The Fourier spectra of the radial component (Figure 7) of the earthquakes recorded at the LNIG show high frequency content, the same behavior was observed at the transversal component spectral. In some cases, there is a flat response between $1 \leq f \leq 10$ Hz. This was observed for the 1, 2, 4, 5, 6, 7, 11, and 13 events (Table 1). Crone *et al*. (2003) mentioned that major intraplate earthquakes can cause widespread damage because the seismic energy attenuation from large earthquakes is relatively low at plate interiors. Figure 8 depicts the average of the spectral ratio *H*/*V* (radial and transversal components) of thirteen weak motion earthquakes recorded in the LNIG. From these figures, it is clear that the mean of the two components have a flat response (amplitude unitary) in the frequency range of 0.2 – 10 Hz. Such behavior corresponds to a rock site and shows that the shale of the Mendez Formation is free of site effects.

## Discussion and Conclusions

In this study several techniques to characterize site effects were used. This was applied in the LNIG station, one of the new seismological observatories that have been recently installed by the SSN. In the definition for the standard reference rock site we evaluated (a) the average of the shear wave for the first 30 m of depth, and (b) the frequency of resonance by means of spectral ratio of microtremors and weak-motion local earthquakes. The $V_{S30}$ value obtained from seismic refraction profiles was 1870 m/s and corresponds to a hard rock site (type A) according

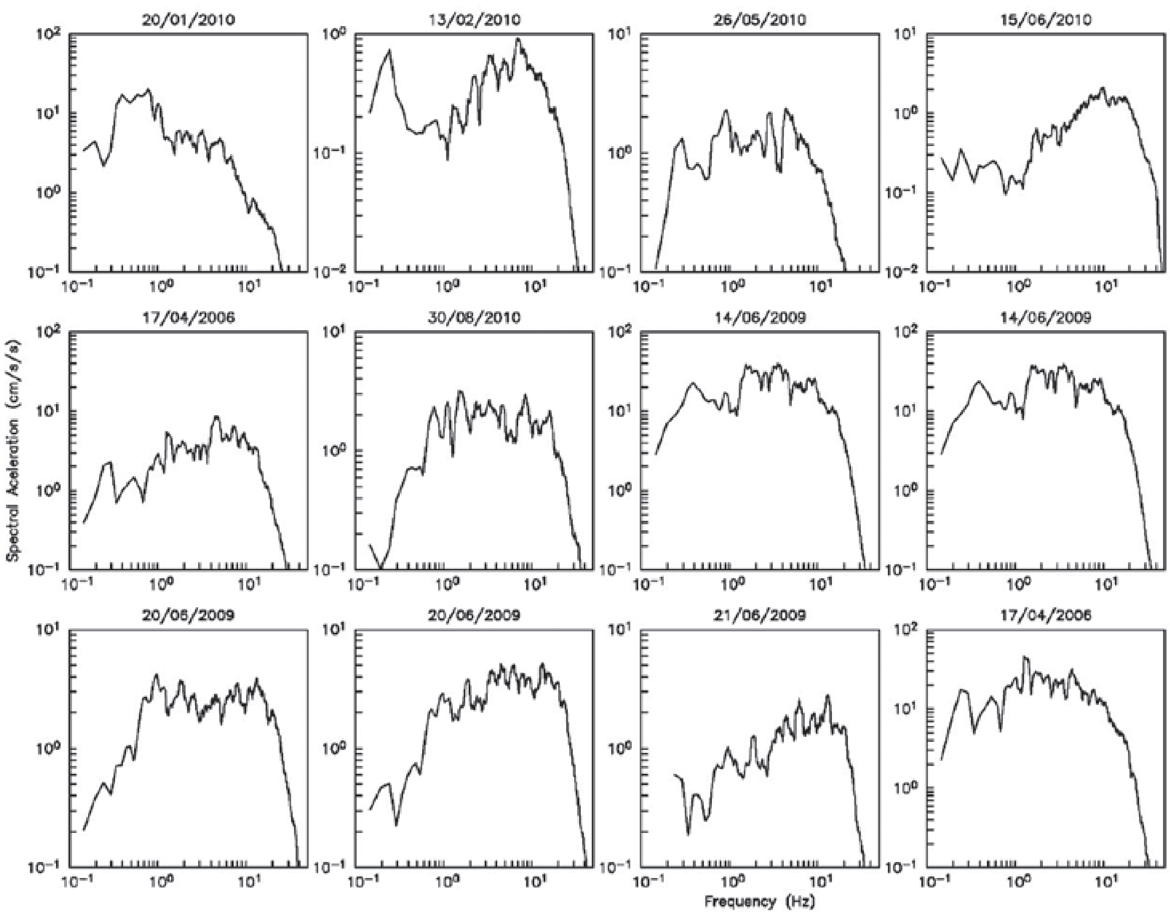


**Figure 7.** Fourier spectra of the radial component of 13 local earthquakes recorded at LNIG site.

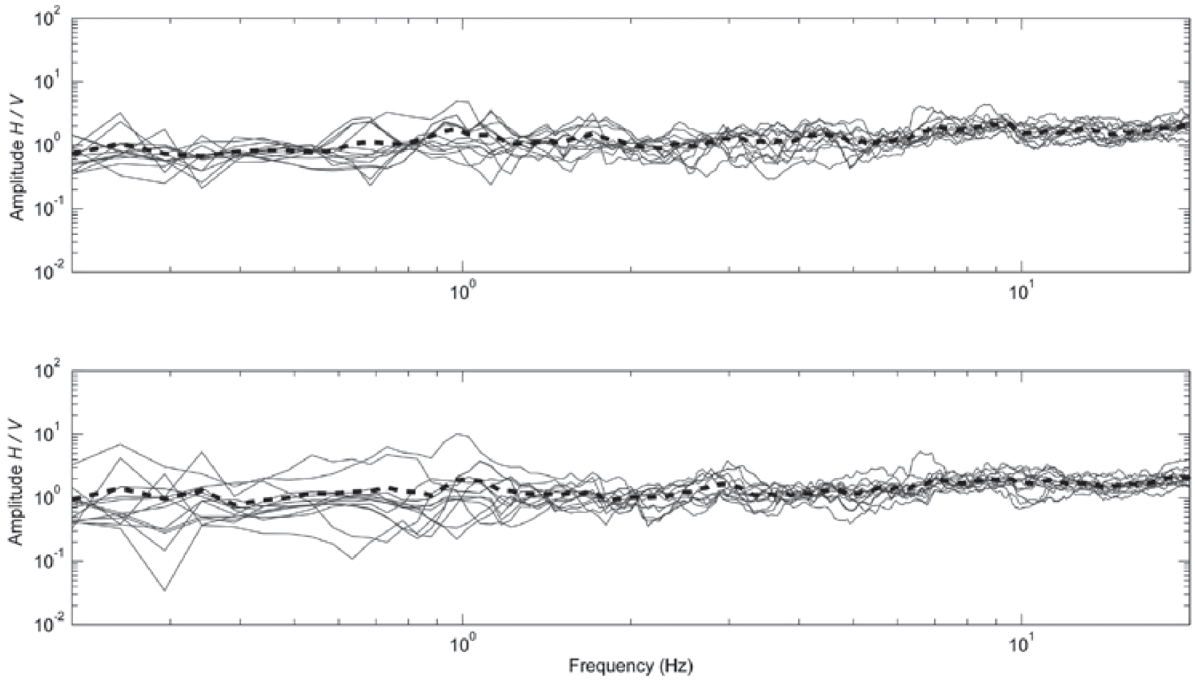


**Figure 8.** Spectral *H/V* ratios of acceleration of 12 local earthquakes recorded at LNIG site. Upper panel: Radial component. Lower panel: Transversal component.

to the NEHRP. On the other hand, the spectral ratios obtained from microtremors and local weak-motion earthquakes have a flat response (unit amplitude) for the frequency range 0.2 to 20 Hz. According to the definition proposed by Steidl *et al*. (1996) and Cadet *et al*. (2010), the LNIG site, located in shale of Mendez Formation, corresponds to a reference site.

The importance of establishing the LNIG as reference site is due to the need of having a seismic permanent station in northern Mexico, that allows monitoring the seismic local activity and is representative in the study of seismic-hazard assessment in a region where the main cities of northeast Mexico are located (the Monterrey Metropolitan Area and Saltillo cities).

Finally, since its installation several local weak–moderate earthquakes have been recorded in the LNIG station. The epicentral location proposed by the SSN locates these events in the Sierra Madre Oriental fold-thrust belt, and the Gulf Coast Plain regions. Some of these events have caused minor damages and moderate shake in localities of Galeana and Montemorelos, N. L. The recompilation of historical seismicity made by some authors and the seismicity recorded by LNIG confirm evidence of more than 245 years of seismic activity in northeast Mexico.

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