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Mapping Seismic Site Classes in Monterrey Metropolitan Area, northeast Mexico

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Abstract

A first microzonation map of seismic site class distribution in Monterrey Metropolitan area is presented. This was prepared using borehole information, seismic refraction profiling and surficial geology. According to geotechnical site categories proposed by Rodriguez-Marek *et al*. (2001) and NEHRP soil classification (V_{S30}), C, C1-C2 sites classes are located to the south and central of the study area. In the northwest zone, B site classes are dominant. Lowest S-wave velocity (average of 268 m/s) correspond to silts, whereas highest velocities (average 2311 m/s) are related to Cretaceous limestones. Maximum thicknesses (16 to 20 m) of the soft sediments C-C2 classes are located at the center area being correlated to two paleo-channels. This study provides an initial attempt to understand and characterize the seismic site classes in the study area.

Key words: seismic *P*-wave velocities, seismic *S*-wave velocities, borehole data, seismic microzonation, seismic refraction profiles

Resumen

En este trabajo se presenta el primer mapa de la distribución de la respuesta sísmica de sitio en el área metropolitana de Monterrey, el cual fue preparado a partir de información de pozos, perfiles de refracción sísmica y geología superficial. De acuerdo con la clasificación geotécnica propuesta por Rodríguez-Marek et al. (2001) y la clasificación de suelos a través de V_{S30} del NEHRP, en la parte central y sur del área en estudio predominan los sitios clase C, C1-C2; mientras que en la zona noroeste los sitios clase B prevalecen. A partir de perfiles de refracción sísmica se determinó que los valores más bajos de propagación de ondas S (promedio 268 m/s) corresponden a limos, mientras que las velocidades más altas (promedio 2311 m/s) se correlacionan con calizas del Cretácico. Los espesores máximos de los sedimentos aluviales (16 a 20 m) se localizan en la parte central del área de estudio y se clasificaron como tipos C-C2, estos espesores se identifican con la presencia de paleocanales.

Palabras claves: Velocidades sísmicas de ondas P, velocidades sísmicas de ondas S, datos de pozos, microzonación sísmica, perfiles sísmicos de refracción.

1. Introduction

Local geological conditions may generate significant amplification of ground motion and concentrate damage during earthquakes. Usually the younger and softer soils amplify ground motion more strongly than older and more consolidated soils or bedrock. Several studies have shown the importance of the upper 30 m on the ground shaking from earthquakes (Montalvo-Arrieta *et al*., 2002). There are numerous works that show strong correlations between ground motion during earthquakes and average shear-wave velocity (e.g., Park and Elrick, 1998; Stewart *et al*., 2003). A simple way to characterize site conditions is by estimating the shear-wave velocity of shallow soils. The average velocity of the first 30 m (V_{S30}) is a widely used parameter to predict the potential amplification of seismic shaking (Holzer *et al*., 2005). This parameter has been used in recent developments of building codes (BSSC, 1997; Dobry *et al*., 2000). A decreasing value of V_{S30} often correlates to an increase in amplification of earthquake ground motion, and with unconsolidated Quaternary deposits (Williams *et al*., 2003). Site classification obtained from shallow shear-wave velocity models is important in deriving strong-motion prediction equations (e.g., Boore *et al*., 1997). In areas of low seismicity and a lack of strong ground motion records, one way to classify the seismic site effect distribution is by means of the correlations between surface geology, borehole data (lithologic) and shear-wave velocity measurements. This approach was used in several areas (e.g., Tinsley and Fumal, 1985; Park and Elrick, 1998; Rodríguez-Marek *et al*., 2001; Stewart *et al*., 2003) to generate local and regional maps (Wills and Silva, 1998; Wills *et al*., 2000) according to site categories of the National Earthquake Hazards Reduction Program (NEHRP) and to predict amplification factors which are included in attenuation relations.

Monterrey and its metropolitan area (hereafter MMA) are located in northeast Mexico, limited by the Sierra Madre Oriental and the Gulf Coastal Plain provinces (Figure 1). Northeast Mexico is generally regarded to as a tectonically stable region, characterized by low seismicity (Figure 1) and a lack of strong ground motion records (Galván-Ramírez and Montalvo-Arrieta, 2008). In northeastern Mexico and the U.S. border region, the main historical earthquakes are the 1887 Bavispe, Sonora (M_W = 7.4; Natali and Sbar, 1982), 1928 Parral, Chihuahua earthquake (M_W = 6.5; Doser and Rodriguez, 1993), 1931 Valentine, Texas earthquake (M_W = 6.4; Doser, 1987), and southwest Texas or Alpine earthquake in April 14, 1995, (M_W 5.7; Xie, 1998; Frohlich and Davis, 2002). Although only about 5% of the global seismic energy is released in continental interiors (Talwani, 1999; Crone *et al*., 2003), the human impact of intraplate earthquakes justify efforts to understand and assess the potential hazards in stable regions. Galván-Ramírez and Montalvo-Arrieta (2008) made a compilation of the historical seismicity in the region.

Galván-Ramírez and Montalvo-Arrieta (2008) mentioned that a possible critical scenario would represent the rupture (M_W = 6.5) of the San Marcos fault south segment in Central Coahuila. The importance of this scenario is the settlement of three of the most populated centers in northeast Mexico (Monterrey, Saltillo and Monclova with a total population of more than six million) located in a radius less than 150 km from the fault source. The damage associated to this hypothetical earthquake could be severe due to the fact that most of the buildings were constructed without seismic criteria. These authors using prediction equation by Toro *et al*. (1997) mentioned that, the expected Peak Ground Acceleration (PGA) values only for rock site obtained for Monterrey, Saltillo and Monclova are between 30 to 70 cm/s^2. On the other hand, this hypothetical earthquake may also produce, or trigger, significant landslides and rock falls in the Sierra Madre Oriental where parts of these cities are located. These cities, as many other urban centers in northern Mexico, have been constructed ignoring seismic criteria. Therefore, it is necessary to design policies to enforce the development of effective risk-reduction programs that include: (a) the level of expected ground shaking estimation, (b) identification of susceptible sites to ground failures, and (c) the production of geographic databases, including the previous information and population distribution, type of materials and building techniques.

The goal of this study is to generate the first distribution of seismic site conditions map for the Monterrey region. To obtain this, we used geotechnical data, seismic refraction profiles and surface geology. This study provides an initial attempt to understand and characterize the seismic site response, as well as the velocity structure, and its distribution in Monterrey city and its surrounding area.

2. Study area

The MMA is the third biggest city in Mexico, known as "the industrial capital of Mexico", with a population of about four million inhabitants (INEGI 2006). MMA is located at the borders of two tectonic provinces: Sierra Madre Oriental and the Gulf Coastal Plain (Figure 1). The Sierra Madre Oriental is a sequence of mainly carbonated and clastic marine sedimentary rocks of Late Jurassic and Cretaceous ages, complexly folded and overthrusted during the Laramide Orogeny (Gomberg *et al*. 1988; Dickinson and Lawton, 2001; English and Johnston, 2004). The Gulf Coastal Plain corresponds to a thick sequence of clastic sediments of Tertiary age characterized by an extensional deformation (Ortiz-Urbilla and Tolson, 2004). Therefore, the MMA morphology corresponds to a wide valley (~ 580 masl) surrounded by mountains with heights of 2100 masl. MMA population is mainly concentrated in the valley, where government offices, service facilities as well as commercial and residential areas are settled. During the last two decades, MMA has experienced an accelerated growth causing urban limits to move beyond the valley, reaching mountain toes

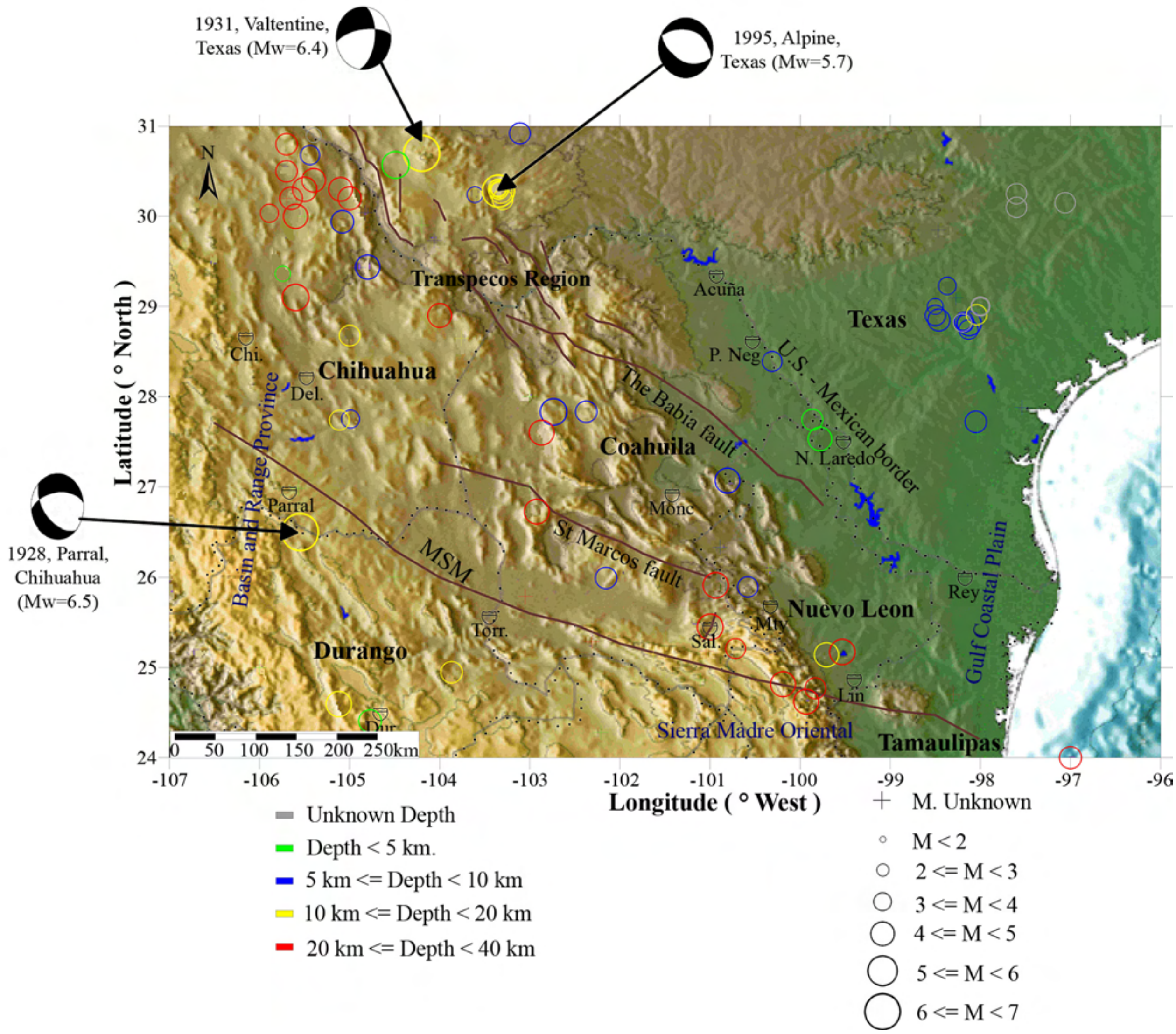

Figure 1. Northeastern Mexico and southern Texas Historic seismicity (1847-2005, Galván-Ramírez, and Montalvo-Arrieta, 2008). Open circles represents the epicentral location of the earthquakes for this period. Solid lines depict the three general north-northwest trending lineaments and faults that have been identified or postulated in northeast Mexico: the La Babia fault, the San Marcos fault, and the Mojave-Sonora megashear (MSM). Triangles indicate some of the larger cities (Acuña; Chi: Chihuahua; Del: Delicias; Parral; Tor: Torreón; Mon: Monclova; Sal: Saltillo; Mty: Monterrey; Lin: Linares; N. Laredo: Nuevo Laredo; P. Neg: Piedras Negras; Rey: Reynosa). Focal mechanisms were obtained from Doser (1987), and Doser and Rodriguez (1993).

and hillslopes (with pronounced slopes prone to landslides during rainfall season).

At present, there is a lack of an integrated work that depicts the valley geometry. The only available information is scarce and disseminated; it is based on geotechnical borehole data (Alva-Niño, 1995; Hernández-Padilla, 1995).

3. Surficial geology

As mentioned before, MMA is located at the frontal part of the Sierra Madre Oriental, North of the Monterrey salient (Padilla y Sánchez, 1982). Sedimentary rocks are composed of limestone and shale outcroppings in the valley borders and mountain ranges. Additionally, these rocks form gently hills in the valley: the La Loma Larga and Loma Linda structures (Figure 2). The first one corresponds to an anticline composed of Mendez Formation shales and San Felipe and Agua Nueva Formation limestones. The Loma Linda is composed of Mendez Formation shales and is located inside a valley delimited by the Cerro de Las Mitras and the Cerro del Topo Chico (Figure 2).

There are overlying discordantly to bedrock, alluvial and fluvial sediments of Tertiary and Quaternary ages. The valley is filled by fluvial and alluvial sediments deposited as terraces during accumulation-erosion cyclic changes (Ruiz-Martínez and Werner, 1997). The most recent sediments are

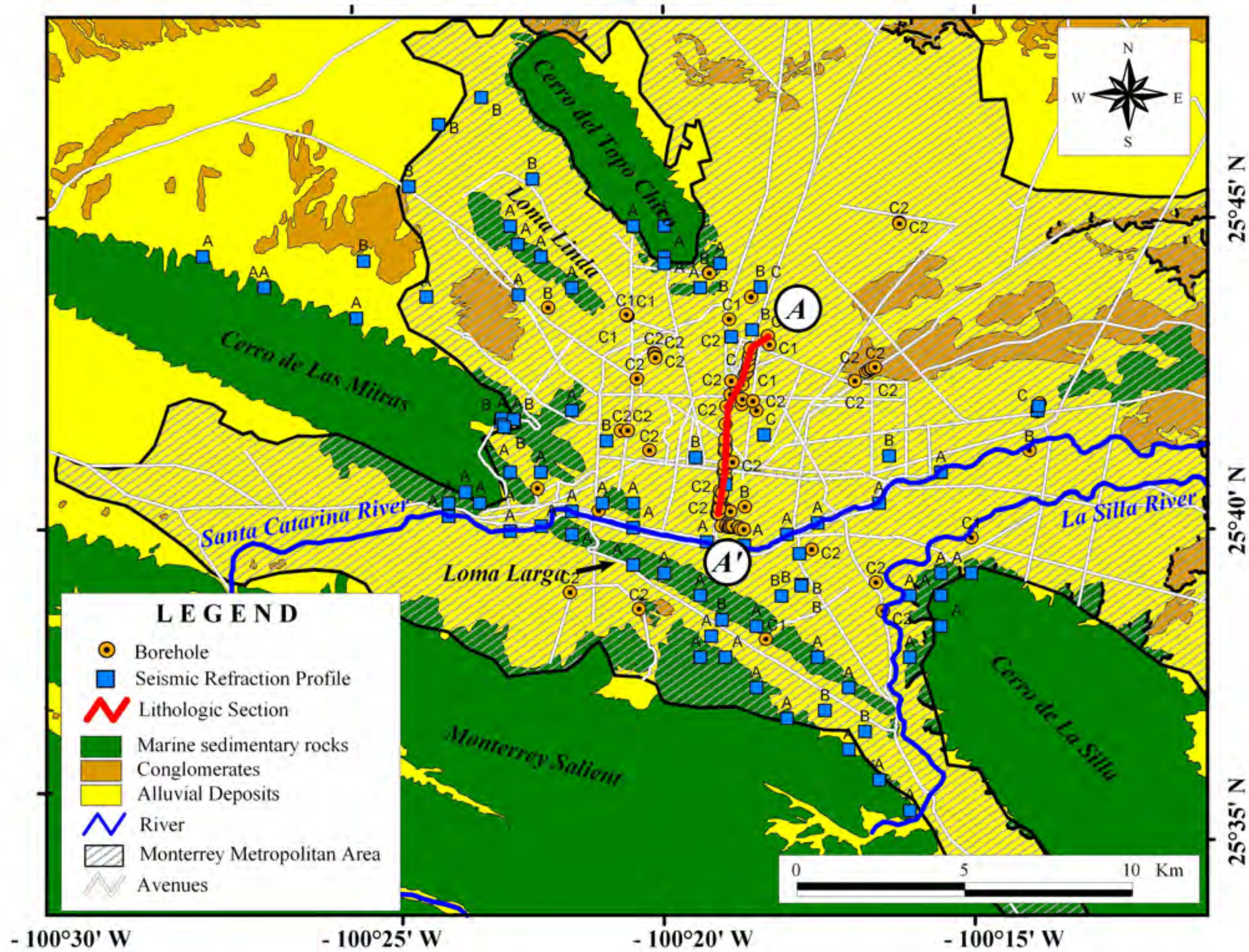

Figure 2. Generalized surficial geology map of the MMA and locations of seismic refraction and borehole sites.

deposited as riverbeds in Santa Catarina and La Silla rivers, both flowing eastward (Figure 2). Fluvial deposit thickness in the valley ranges from 18 - 24 meters and it is due to the presence of paleochannels as a result of meandering river courses (braided-streams). Alluvial deposits are constituted by uncemented and unweathered cobble to small pebble gravel, gravelly sand, sand and silts, locally cemented in modern washes by calcite cement.

During the construction of the first MMA subway transect (1987-1991), a geotechnical characterization was done through borehole drillings. Several caves were identified in the valley center just beneath government offices, schools and hospitals (Alva-Niño, 1995). These chemical dissolution structures are several meters in diameter and are related to karstification processes.

Based on surficial geology and morphology, the study area can be subdivided into three regions: southern, central, and northwestern. The southern and central zones are naturally separated by the La Loma Larga hill. The northwestern portion is situated between the El Cerro de las Mitras and the Cerro del Topo Chico (Figure 2). Thickness variation of unconsolidated sediments in central zone is shown by the geological cross section (A-A') constructed from borehole data (Figure 3).

The south-north oriented cross section A-A' shows with more detail the variations of the geometry due to the density of borehole data shown in Figure 2. This section is dominated by silts, alluvial and shale deposits, reaching its maximum thickness (about 20 m) between the boreholes BD7 - BD8 and BD14 - BD15. In the section extremes, the thickness layer diminish to 10 m. Alluvial deposits are composed of gravel (uncemented and partially cemented), gravelly sand and sand. Strong cementation is observed between boreholes BD18 – BD12 and in depths > 10 m (Alva-Niño, 1995). Other sites related to terraces (alluvium) occur in the southern area and near the Cerro de la Silla, where its thickness is greater than 15 m.

4. Geotechnical data

Rodriguez-Marek *et al*. (2001) recently proposed

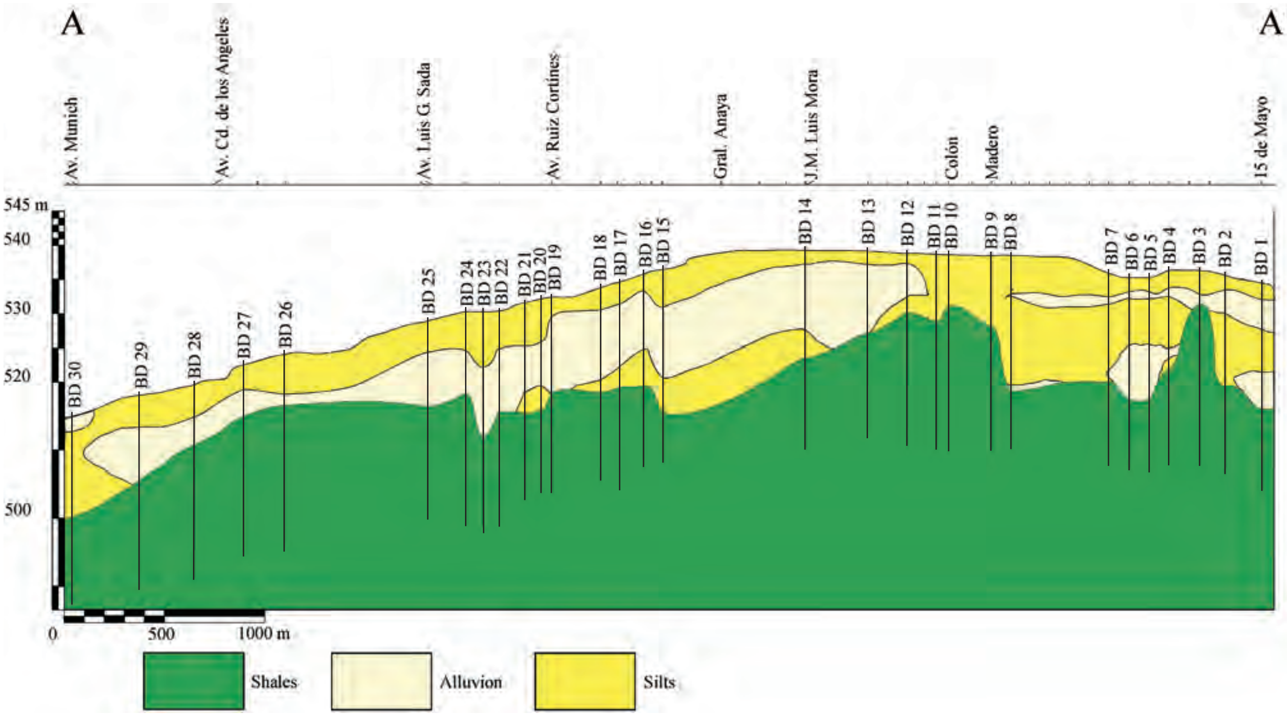

Figure 3. Geologic cross section in S-N direction (A-A') of the distribution of shallow sediments in the MMA, obtained from borehole and seismic refraction data.

geotechnical classification schemes as alternative to evaluate seismic site response, based on results from the ground motion data analysis from the 1989 Loma Prieta and 1994 Northridge earthquakes. We used the site classification schemes (Table 1) proposed by Rodriguez-Marek *et al*. (2001) to analyse the 95 borehole data located in MMA. Figure 2 shows the distribution and classification of the boreholes. As seen in Figure 3, the Quaternary deposits are formed by silts, sands and gravels partially cemented, and in some locations clays product of the weathering of shales are present. The geologic crosses section A-A' was constructed from 30 borehole data. At site BD3 the alluvial deposits are diminished due to uplift of bedrock, which according to Rodriguez-Marek classification corresponds to a site class B. The distribution of the borehole data in the central zone of the study area permits us to characterize the site conditions and distribution in MMA downtown area. Entire borehole data reach the bedrock at different depths; the maximum thickness of Quaternary sediments in the valley is 24 m. From 95 borehole data 74 correspond to site class C2 (soil depth > 6 m and < 30 m), 12 are related to site class C1 [weathered zone > 6 m and < 30 m (Vs > 360 m/s increasing to > 700 m/s)], and only 9 correspond to site class B (soil depth < 6 m). Sites C1 are located near Loma Linda and Cerro del Topo Chico hills and correspond to a diminished of the thickness of Quaternary sediments.

Table 1. Geotechnical site categories proposed by Rodriguez-Marek *et al*. (2001)

Site	Description	Comments
A	Hard Rock	Hard, strong, intact rock; $V_S \geq 1500$ m/s
B	Rock	$V_S \geq 600$ m/s or < 6 m of soil
C1	Weathered/Soft Rock	$V_S \geq 300$ m/s increasing to 600 m/s, weathering zone > 6 m and < 30 m
C2	Shallow Stiff Soil	Soil depth > 6 m and < 30 m
C3	Intermediate Depth Stiff	Soil depth > 30 m and < 60 m
D1	Deep Stiff Holocene Soil	Depth > 60 m and < 200 m
D2	Deep Stiff Pleistocene Soil	Depth > 60 m and < 200 m
D3	Very Deep Stiff Soil	Depth > 200 m
E1	Medium Depth Soft Clay	Thickness of soft clay layer 3-12 m
E2	Deep Soft Clay	Thickness of soft clay layer > 12 m
F	Potentially Liquefiable Sand	Holocene loose san with high water table ($Z_W \leq 6$m)

Additionally, we made seismic refraction profiles to obtain the seismic velocities of some sites in MMA. These shear wave velocities data permitted us to correlate surface geology, geotechnical site categories, and seismic velocity structures to develop the first seismic site classification MMA map.

5. Seismic data

Seismic velocity structure of the upper 30 m was determined at 37 locations in the MMA by using seismic refraction. Seismic refraction data were interpreted using travel-time curves (slope-intercept method). For this method, we picked first-arrival phases assumed to be refracted from the same interface, and calculated the velocity from the slope of the line connecting these phases. Velocities were computed from the line slope connecting arrivals, assuming that the velocity is constant along the profile. A RAS-24 Remote Acquisition System with 24-bit A/D conversion in a 24 channel box was used, with horizontal and vertical geophones with natural frequency of 28 Hz, and a sledgehammer as seismic source. As the study area is highly urbanized, it is difficult to obtain adequate sites for seismic refraction profiles. Thirty seven seismic refraction profiles were registered in city parks in residential areas, public land or industrial areas. Most sites were chosen to sample the primary surficial geologic units (silts, alluvium, conglomerates and bedrock formed by shales and/or limestones) with emphasis on the more populated areas.

Geophone array had variable intervals of 1.0, 2.0, 4.0, 5.0, 8.0 and 10 m, for both P and S waves, in direct and inverse profiles. These configurations were used depending on the characteristic of the site, mainly at places where we do not have information about thickness, to obtain a realistic velocity structure. Taking into account the geophone array dimension, a maximum penetration of 40 m was attained. For example, at the Hospital Universitario (PR5) located in the center of the valley, we used a geophone interval separation of 1, 5 and 8 m. Figure 4 depicts the seismograms with an interval separation of 5 m and the velocities obtained for P and S waves. Figure 5 shows the seismic velocity structure resulting (for P and S waves) the interpretation of each seismogram at PR5. At this site, four different materials were identified (silts, alluvium, fractured and unaltered shales) with the following velocities: 230, 470, 1705 and 2080 m/s for S waves, and 400, 823, 2140 and 2820 m/s for P waves (Figure 5). In this work we accept that the maximum error associated in the determination of velocities from slope methods is about 5 percent (10 % for noisy data). This range of error may affect the accuracy of the layer thickness calculation in about 10 to 20 percent. Figure 6 shows the seismic velocity structure for the Rio Santa Catarina (PR16) site. This location corresponds to shallow riverbed sands and gravels overlying shale bedrock. We identified only

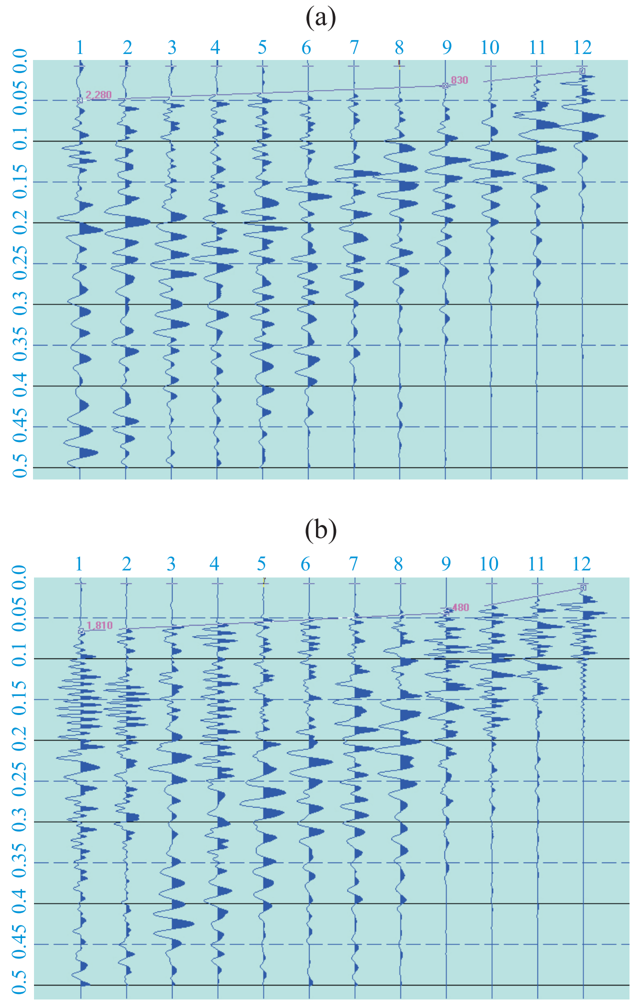

Figure 4. (a) P wave seismic refraction profile at PR5 site (Hospital Universitario, central area), the interval of separation between geophones is 5 m (55 m of longitude) and 0.5 s of record length. The seismic velocities obtained were: 830 and 2280 m/s, respectively; (b) S wave seismic refraction profile, the interval of separation between geophones is 5 m (55 m of longitude) and 0.5 s of record length, with velocities of 480 and 1810 m/s, respectively

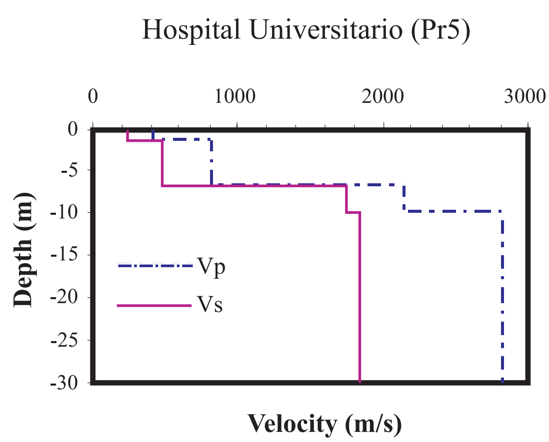

Figure 5. Velocity structure (P and S waves) at PR5 site (Hospital Universitario, central area) obtained from seismic refraction profiles.

two lithologic units, fluvial deposits with velocities of 830 m/s for S waves and 1250 m/s for P waves; and shales with velocities of 1900 m/s to S waves and 3330 for P waves. We obtained seismic velocity structures (P and S waves) for all seismic refraction profiles, and we found that in almost all cases the thickness of the soil (silts, alluvium, in some places clays, and conglomerates) were less than 15 meters. The lowest velocities obtained were located at the valley centre, while the higher velocities correspond to bedrock sites (shales units). Some seismic refraction profiles were located near valley borders and hill slopes where limestones outcroppings appear (Figure 2).

Table 2 shows the average results for P and S waves obtained from the five lithologic units: limestones, shales, conglomerates, gravels and silts, and the number of profiles in each unit. Detailed velocity structure for all seismic refraction data profiles is available in Cavazos Tovar (2007). P and S wave velocity average obtained for MMA represents the first contribution to understand the behaviour and distribution of the seismic velocities in the lithologic units (Quaternary, Tertiary, and Mesozoic) with emphasis on soil classifications. The lower velocities correspond to silt (Quaternary) with an average of 268 m/s and 433 m/s for S and P waves respectively, and the higher velocities (2311 m/s and 3684 m/s for S and P waves) are associated to the limestones (Mesozoic) that are located at the hills Cerro de Las Mitras and the Cerro del Topo Chico. The bedrock in the valley is represented by shales (Mesozoic) with mean velocities of 1774 m/s and 2783 m/s for S and P waves, whereas the alluvial deposits have mean velocities of 632 m/s and 1064 m/s for S and P waves.

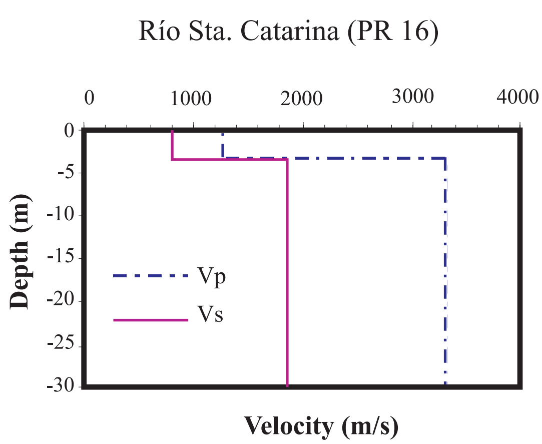

Figure 6. Velocity structure (P and S waves) at PR16 site (Río Santa Catarina) obtained from seismic refraction profiles

We measured some seismic profiles near the boreholes. Thicknesses determined from seismic velocity structure are very close to the borehole data lithologic description. Therefore, P and S wave velocities of surficial material can be correlated to the same type of material at depth. Figure 7 compares the seismic velocity structure to the borehole data for PS2 site. A seismic refraction profile was carried out near the borehole (< 1 m for the site), at this site the velocity structure for P and S waves was determined obtaining four layers composed of clays-silts and clay-shales. The velocity structure generated through seismic refraction profile, show that the seismic velocity variations are concordant with thickness and lithology changes reported in borehole descriptions. Also, the sediment consolidation degree increases with depth in the same way as the seismic velocity gradient increases (Figure 7). This process of sediment consolidation is due to calcite cementation of alluvium (caliche) which generates increases in seismic velocities in Quaternary alluvium. Similar behaviour between increases of seismic velocities and lithologic units with cementation were reported in other areas near MMA by Montalvo-Arrieta *et al*. (2005), where alluvium and conglomerated have mean values of 559 and 1220 m/s for S-waves and 957 and 2471 m/s for P-waves respectively. The increase of the seismic velocity with depth is verified with seismic tomography in three boreholes in the Linares area (Piccioto-Fernandez, 2000). This author obtained three velocity structures (P waves) for each borehole using a "sparker" source located at different depths in boreholes that cut shales of Mendez Formation. Piccioto-Fernandez's results show an increase of seismic velocity of 3200 m/s at 10 m to 5400 m/s at a depth of 45 m, for MMA the range of seismic waves for the Mendez Formation are 1200 to 2500 for S waves and 2140 to 3750 for P waves.

According to NEHRP building codes, soil conditions were classified in six different groups (Table 3). As mentioned by Holzer *et al*. (2005), this classification is widely used in the United States and has been incorporated

Table 2. Average of P and S waves for the different geological units in the study area. N represent the total number of seismic refraction profiles in each unit.

N	Geological unit	V_{Smin}	V_{Smean}	V_{Smax}	V_{Pmin}	V_{Pmean}	V_{Pmax}
12	Silts (Recent)	180	268	390	270	433	590
20	Alluvium (Quaternary)	360	632	1015	575	1064	1660
9	Conglomerate (Tertiary)	1200	1370	1460	2330	2403	2500
15	Shales (Upper Cretaceous)	1200	1774	2500	2140	2783	3750
5	Limestone (Upper Cretaceous)	1890	2311	3000	3270	3684	4400

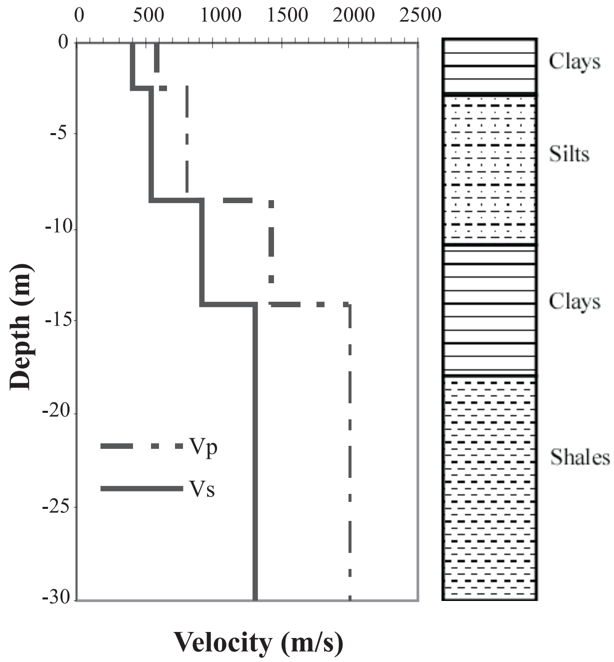

Figure 7. Comparison between seismic velocity structure and borehole data (lithologic units) obtained at PS2 site. For this case the separation between the centre of seismic refraction profile and the borehole site was < 1 m.

into many buildings codes around the world. In this work, NEHRP classification scheme has been used to estimate the average shear-wave velocity (V_{S30}) as indicator of site response:

$$V_{S30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{Si}}} \tag{1}$$

Where d_i is the thickness of the i^{th} layer between 0 and 30 m and V_{Si} is the shear-wave velocity layer in the i^{th} layer (Borcherdt, 1994; Williams *et al*., 2003; Boore, 2004). The two main limitations of seismic refraction profiles interpretation techniques are: an assumption that layer velocity is constant across the length of the profile, and lower velocity layers underlying a high velocity layer can be detected, but no measured. However, in spite of these assumptions several authors have shown agreement with seismic velocity downhole profiles, determined from measurements in shallow boreholes in California and Memphis, Tennesse (Williams *et al*., 1997; Williams *et al*., 2003). For northeast Mexico, Montalvo-Arrieta *et al*. (2005) and Piccioto-Fernandez (2000) have found evidence in the Linares area (region with similar geological conditions as MMA) that the seismic velocities are increased with depth

Table 3. Site classifications using V_{S30} as an indicator of site response (NEHRP).

Soil	Profile Type	Rock/Soil Description (m/s)
A	Hard rock	> 1500
B	Rock	760-1500
C	Very dense soil/soft rock	360-760
D	Stiff soil	180-360
E	Soft soil	< 180
F	Special soils requiring site-specific evaluation	

due to the characteristics of the geologic units buried trough surficial seismic refraction profiles and seismic tomography in boreholes. So, although V_{S30} is not the only parameter to define seismic site response, it can be used in an attempt to understand and characterize the seismic site response, as well as the velocity structure in an area with scatter seismic information as MMA.

We estimated the V_{S30} values of 37 seismic refraction profiles to obtain the seismic site class distribution according to NEHRP and correlated to the site geotechnical class obtained from borehole data, to generate the first seismic site class distribution map for MMA. The V_{S30} values for each seismic refraction profile were obtained from the seismic velocity structure generated by every seismic profile (e.g. Figures 5, 6 and 7) using equation (1). There are good correlations between the V_{S30} values and the geotechnical classification. Figure 7 shows the comparison between borehole data and seismic refraction profile at PS2 site, V_{S30} data correspond to site class C (V_{S30} = 716 m/s) and the borehole data have a C2 geotechnical classification (soil thickness equals 16 m).

6. Map of seismic site classes in MMA

Figure 8 shows the first seismic site distribution map for MMA in the upper 30 m. It was prepared by the interpolation of seismic refraction data (V_{S30}) and borehole data (Rodriguez-Marek's geotechnical classification) in geologic maps (CETENAL, 1976) scale 1:50,000. We assigned the average V_{S30} (site class A NEHRP) obtained for limestones in Cerro de Las Mitras to the Loma Larga, Cerro del Topo Chico and Cerro de La Silla where the same type of rock outcropped. This information was integrated into the Geographic Information System (GIS). We found a good correlation between V_{S30} values, geotechnical classification, and the soil units description.

The low velocity sites (V_{S30} = 471 m/s) are related to alluvial debris thick horizons and recent soils which correspond to C site class materials. In the southern part, a small area with site class C2 was identified in front of the Monterrey salient. This spot is characterized by the

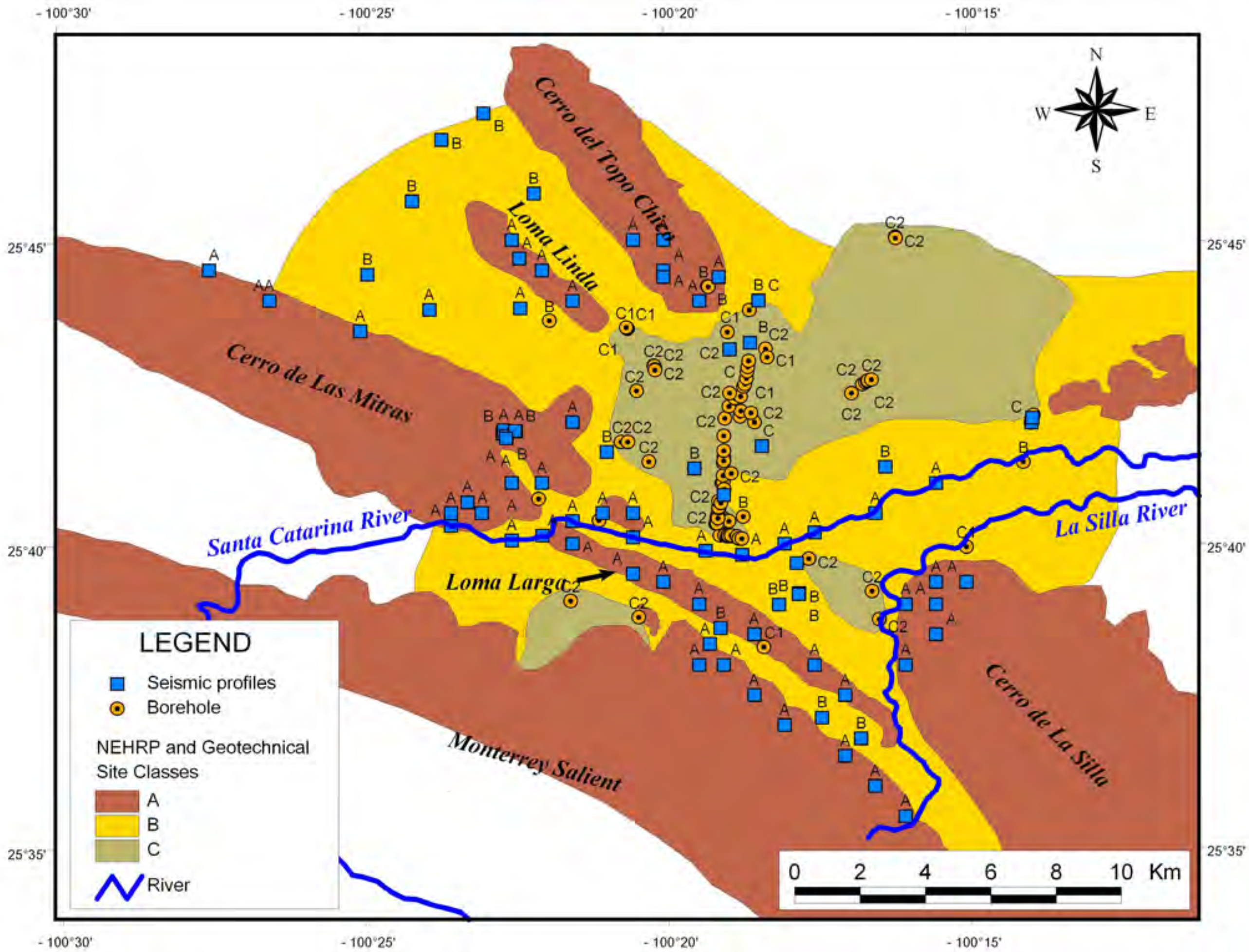

Figure 8. Composite seismic site distribution map from V_{S30} and geotechnical site classification for the Monterrey Metropolitan Area, obtained from seismic refraction profiles and borehole data in geologic maps (CETENAL, 1976) scale 1:50 000.

accumulation of materials eroded from ranges (alluvial fans). The same case is found in the northwest of Cerro de la Silla, where three boreholes correspond to site class C2. The more extensive zone corresponds to the central area (downtown), where low V_{S30} values and geotechnical site classes C1-C2 were obtained from borehole data and correlated to alluvial and fluvial deposits. These yield the maximum thickness of the Quaternary sediments (soil depth > 6 m and < 30 m). The northwestern area represents the accumulation of alluvial material originated from the Las Mitras and Topo Chico ranges. In this portion, the site class B is predominant due to a thin layer of unconsolidated sediments (gravel partially cemented).

By contrast, the high V_{S30} velocities (760 – 2200 m/s) were determined in all three areas where shallow bedrock is present, e.g. near mountains, suggesting thick sequences of well-graded large clasts, such as boulders or cobbles, or very weak and fractured rock near the surface. The site classification for these places is A/B. Other places with these characteristics occur near both rivers where the loose sediments have thickness less than 5 m.

Recently, Montalvo-Arrieta *et al*. (2008) used the seismic velocity structures obtained from seismic refraction profiles and the thickness of the borehole data presented here, to obtain 1D seismic site response and compare them with spectral ratios H/V of microtremors recordings. They found the maximum spectral amplitudes between 3 to 6 times, which are related with a range of frequencies of 3 to 6 Hz respectively.

7. Conclusions

In this work, a first seismic soil classification map is presented for building purposes in MMA through V_{S30} and geotechnical seismic site classes. The presence and distribution of materials susceptible for ground shaking amplification are identified through the integration of seismic refraction profiling correlated to borehole information.

A seismic velocity classification for different lithologic units outcropping in the study area (silts, alluvium, conglomerates, shales and limestones) has been integrated for the first time. The lowest values of S waves (average of 268 m/s) correspond to silts, whereas the highest velocities (average 2311 m/s) are related to Cretaceous limestones. According to NEHRP and geotechnical soil classification, A, B, C-C2 site classes are predominant in MMA. C and C2 sites classes are located in the central part and at some places in the southern area. In the northwest zone A and B site classes are dominant, which are correlated to hard rock and rock. Maximum thicknesses (16 to 24 m) of the soft sediments class C2 are observed in MMA downtown, being correlated to paleo-channels.

As observed in Figure 8, in the central area of the MMA valley the seismic site response (NEHRP and geotechnical classification) corresponds to site classes C-C2. The lowest V_{S30} values are above 471 m/s and are linked to geotechnical classification C1-C2 class that correspond to soils with depth > 6 m and < 30 m. These high values of V_{S30} are a result of a cementation of alluvium by calcite (a.k.a. caliche). The lowest values of V_{S30} in MMA correspond to site class C (V_{S30} = 360 – 760 m/s), which are correlated to recent soils and Quaternary alluvium.

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