

Geotechnical Seismic Vulnerability Assessment of Puerto Vallarta, México

Christian R Escudero (✉ christian.escudero@cuc.udg.mx)

Universidad de Guadalajara <https://orcid.org/0000-0002-2437-423X>

Alejandro Ramirez Gaytan

Universidad de Guadalajara

Araceli Zamora Camacho

Universidad de Guadalajara

Adolfo Preciado

ITESO: Instituto Tecnológico y de Estudios Superiores de Occidente

Karen L. Flores

Universidad de Guadalajara

Adan Gomez Hernandez

Universidad de Guadalajara

Research Article

Keywords: Geotechnical zonation, structural zonation, Puerto Vallarta, site classification, Surface waves

Posted Date: March 19th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-325281/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Natural Hazards on July 30th, 2021. See the published version at <https://doi.org/10.1007/s11069-021-04945-w>.

Abstract

We performed a seismic vulnerability assessment that involves geotechnical and building structure analysis for Puerto Vallarta, Mexico, a city located along the Pacific coast. Like many other Latin American cities, has significant seismic risk. We implemented the multi-channel analysis of surface waves and the horizontal-to-vertical spectral ratio methods to estimate shear wave velocity and soil resonance frequency. We considered standard penetration test to determine the penetration resistance and soil classification. We also defined building typologies based on construction materials and structural systems. The VS30 parameter shows that Puerto Vallarta has the three poorest soil classifications. The resonance frequency parameter shows four zones with different fundamental soil periods. We inferred the building's vulnerability from the coupling between the structural and soil fundamental period and the soil characteristics. The analysis shows several vulnerable buildings scattered within the city, e.g., within the tourist area, confined masonry buildings from one to five stories and moment resistance frame buildings up to 12 in the tourist area, poorly confined masonry houses of one to two stories, and confined masonry buildings of one to five stories in the residential/commercial. We present an approach that combines the academic and government to solve a real and transcendental problem since it might directly affect the regulation and structure evaluations in the area. We are sure that these exercises are of great interest in urban growth areas in other parts of the world, especially in Latin America, to achieve seismic risk mitigation.

1. Introduction

We present a multidisciplinary seismic vulnerability assessment that involves geotechnical and building structure data analysis from the civil engineering point of view and data analysis from the geophysical perspective. We performed the analysis for a city located along the Mexican Pacific coast that like many other Latin American cities looks to have significant seismic risk levels. Nevertheless, there is a lack of the necessary research for proper seismic assessment. In this way, we implement an approach that uses data from local authorities (i.e., civil protection) and geophysical data to provide a seismic vulnerability assessment.

The studied area, Puerto Vallarta city, is located within a very active seismic zone (Fig. 1), with a convergent tectonic configuration, i.e., Rivera-Cocos-North American plate subduction system (Stock and Lee 1994). And, continental fragmentation produced extensional systems, i.e., the Colima and the Tepic-Zacoalco rift (e.g., Allan 1986; Bandy et al. 1995; Luhr et al. 1985). These tectonic conditions produced important subduction and intraplate earthquakes.

The most significant historic earthquake in Mexico struck on June 3, 1932, with a magnitude of 8.2 and a rupture extended from the Puerto Vallarta city, at the north, to Manzanillo towards the south (Kelleher et al. 1973). Later on October 9, 1995, an 8.0 magnitude earthquake struck the southern coast of Jalisco, with a ruptured of only half of the 1932 earthquake (Courboulex et al. 1997), supporting the existence of a seismic gap in the northern Jalisco coast (Singh et al. 1981). Approximately 48 earthquakes greater

than 6.0-magnitude had struck in the region from the 1800s to the present (Fig. 1). Site effects enlarge the impact of the earthquake activity.

Puerto Vallarta city is located in the southern part of the Valle de Banderas Graben (Fig. 1), an onshore, sediment-filled, topographic depression formed by the Tepic-Zacoalco rift branching along the Río Ameca (Johnson and Harrinson 1990). In this way, much of the Puerto Vallarta city is built on a complex cover of geologically young deposits of beach and river sands and gravels, as well as estuarine silts. Additionally, Puerto Vallarta geomorphology has been modified with anthropogenic and natural processes changing subsurface materials' stiffness.

According to the National Institute of Statistics and Geography (INEGI 2121) national censuses and counts 2020, Puerto Vallarta's municipality has 291,839 inhabitants, showing an increase of 7.8 percent in five years. The tourism industry has increased over the years and makes up to 50% of the economic activity. There are no official numbers of the floating population; however, we can infer it from the passenger traffic that reaches 57,000 passengers per month through January to March and 222,000 from July to August, from which 73% of the passengers are international. The tourist industry's substantial growth causes land-use changes, transforming natural areas to urban zones for hotels and housing construction and providing services. However, the increase in territorial demand exceeds the competent authorities' planning and territorial ordering capacity, increasing seismic vulnerability.

Puerto Vallarta is an important tourist city undergoing fast development. However, in spite of the seismic activity, subsoil characteristics and the exposed elements, no seismic microzonation has been performed. Therefore, there is a great necessity to elaborate a comprehensive seismic microzonation to contribute in the development of seismological hazard and risk assessment, to provide useful data for construction codes, regulations, and for the retrofitting of existing buildings. Moreover, several examples worldwide have shown that near-surface sediments can significantly amplify ground shaking due to seismic waves. Therefore it is imperative to characterize the subsoil of areas exposed to seismic hazard and prone to site amplification. Available geotechnical and geophysical studies of Puerto Vallarta city are sparse or lack the necessary resolution to estimate seismic site response used as part of earthquake hazard mitigation. Therefore considering the particularities of Puerto Vallarta soils and the questionable use of traditional geotechnical methods, in this work, we applied the MASW and H/V methodologies to estimate the geophysical parameter V_{s30} , the horizontal-to-vertical spectral ratio (HVSr), and fundamental period, T_s , of the subsoil.

In this work, we combined geophysical techniques to estimate subsoil properties and field observations of building structure conditions to infer seismic vulnerability. We applied the Multichannel Analyses of Surface Waves (MASW) and the microtremor horizontal-to-vertical spectral ratio (HVSr) methods to estimate shear wave velocity (Park et al. 2007) and the primary resonance frequency of soft sediments overlaying stiff geological bedrock (Nakamura 1989). The soil classification based on these parameters is fundamental to assess soil–structure resonance that can significantly amplify the seismic damage. We also considered the Standard Penetration Test (SPT), a simple testing procedure, to determine

geotechnical parameters by measuring the standard penetration resistance (SPTN) and determining the soil classification by analyzing collected samples. The correlation of geophysical data with in situ tests provides a better understanding of the seismic vulnerability.

In this paper, we present an approach that combines the academic and local authorities as part of the solution of a real and transcendental problem, i.e., seismic hazard and risk, since this work might directly affect the regulation and evaluations of the structures in the area. We are sure that these types of exercises are of great interest in urban growth areas in other parts of the world, especially in Latin America, to achieve seismic risk mitigation.

2. Puerto Vallarta Topsoil And Subsoil

The region has intense fluvial activity, estuaries environments, and coastal activity that dominated the subsoil production and several anthropogenic landfills. Consequently, Puerto Vallarta has highly heterogeneous topsoil and subsoil. The only local topsoil classification study was published by the National Institute of Statistics and Geography (INEGI 2021). The data was sampled between 2002 and 2006, and the soil was classified based on the World Reference Base for Soil Resources, WRBSR (IUSS 2015). Puerto Vallarta has seven soil types (Fig. 2a), i.e., Cambisol at the east of the city, Fluvisol along the Ameca River, Gleysol surround the estuary El Salado, Leptosol on the mountain areas, Phaeozem, Regosol on the mountain areas, Solonchak within the coast and estuary areas. Figure 2b shows the basement in Puerto Vallarta is mainly composed of Quaternary Alluvium around the river flood zone, Cretaceous silica tuff, and Tertiary conglomerate (INEGI, 2021). It is worth notice that the estuary El Salado is currently located in a relatively small natural protected area (Fig. 1), it just to cover a larger territory.

There are no previous published geophysical characterization studies of subsoil at Puerto Vallarta city. However, Arzate et al. (2006) published a geophysical model of the Valle de Banderas Graben (Fig. 1). Although the scope of the Arzate et al. (2006) study was providing new insights of the structural configuration of the graben, it provides a glimpse to the subsoil structure. A gravity survey was carried out with the purpose of modeling the basement. Results showed that closet to the shore the graben has a wide-basin geometry relatively shallow at the Puerto Vallarta location towards the mountains where the basement outcrops. The maximum thickness estimated for the sedimentary layer at the mouth of the valley is about 2.5 km. Arzate et al. (2006) also performed magnetotelluric, resistivity, and aeromagnetic surveys that corroborate the sediment depth. However, the results do not provided further subsoil information mainly because of the resolution of the surveys. It is worth notice, that these geophysical studies showed a faulted basement beneath the sediment.

3. Materials And Method

The approach consisted of geophysical techniques to estimate subsoil properties and field observations of building structure conditions to infer seismic vulnerability. From the geophysical perspective, working

in an urban environment involves several challenges for seismic field measurements due to the sources, the noise, and the array geometry. Therefore, we implement techniques suitable for urban conditions, i.e., the Multichannel Analysis of Surface Waves (MASW) an active seismic methodology and the Horizontal-Vertical Spectral Ratio (HVSr) a passive seismic analysis methodology. Urban environments also have advantages, such as information from studies of private companies and individuals that have to be performed prior the development of civil engineering infrastructure. And in some cases regulations require that local authorities keep the reports of those studies. In this study, civil protection (CP), “Coordinación Municipal de Protección Civil y Bomberos, Puerto Vallarta, Jalisco” provides several reports of soil mechanics studies. It is important to notice that the geophysical studies were performed with their indispensable collaboration. In addition to the subsoil information, we considered the structural conditions of the building inventory of Puerto Vallarta.

3.1 Multichannel Analysis of Surface Waves (MASW)

The site geotechnical and geophysical characterization is essential for the seismic and dynamic design of civil engineering projects. For design purposes, is necessary the site classification based on shear wave velocity profiles. In the MASW method, Rayleigh waves are generated and used to estimate the shear wave velocity profile of a test site as a function of depth. Compared to other geophysical and geotechnical methods, the MASW method is non-invasive, environmentally friendly in an urban environment, and low-cost. The MASW method is base on the dispersive nature of Rayleigh waves in a vertically heterogeneous medium. It estimates the frequency-dependent phase velocity of the Rayleigh waves or dispersion curve, which is related to soil properties. In particular, the shear wave velocity profile can be determined from the inversion of the experimental dispersion curve (Park et al. 1999). According to Park et al. (1999), the MASW method consists of three steps, i.e., multichannel seismic records acquisition, Rayleigh waves dispersion curves estimation, and dispersion curves inversion to estimate the one-dimensional shear velocity profiles. Fig. 3 shows an example of the data recorded with 24 vertical geophones (left) and the estimated velocity profile at location COPV.

The shear wave velocity profile provides relevant information about the geotechnical properties of near-surface materials. The shear wave velocity profile of the uppermost 30 meters is of most interest because civil engineering structures interact with that subsoil portion. Engineers can use the shear wave velocity profile, for example, to evaluate the stiffness of the topmost soil layers and to evaluate liquefaction and soil amplification potential. The European Standard of Design of Structures for Earthquake Resistance (EUROCODE 8) and the National Earthquake Hazard Reduction Program, NEHRP, proposed the V_{S30} parameter for soil classification. The V_{S30} parameter is defined as the average seismic shear wave velocity between the surface and 30 m depth (Borcherdt 2012). Borcherdt (1992, 1994) proposed the V_{S30} parameter for the estimation of site-dependent response spectra according to NEHRP (BSSC 2009). V_{S30} is a well-accepted and robust parameter to characterize local site response and define seismic zoning within an urban area. The V_{S30} is obtained using the following equation:

$$V_S = \frac{\sum_{i=1}^n d_i}{\sum_{i=1}^n \frac{d_i}{V_{si}}} \quad (1)$$

Where corresponds to the thickness of the i -th layer between 0 to 30 m depth; and is the shear wave velocity of the i -th layer in m/s. In Table 1 we show the soil type classification according to the NEHRP (BSSC 2009). For this study, we obtain the V_{S30} values from shallow-surface 2D velocity profiles, V_S -*depth*, estimated from the seismic noise analysis using the MASW method.

We chose 52 recording sites evenly distributed over the city of Puerto Vallarta (Fig. 1 and Table 2). The seismic records were performed using a 24 channels Geode seismograph from Geometrics and 24 geophones with a natural frequency of 4.5 Hz, damping of 50%, cut-off frequency of 80 Hz, and a sensibility of 0.7 V/in/sec. The active source was a 35 kg iron sphere released from an approximate height of two meters. We deployed liner arrays with a source offset of 10 meters and two meters geophone distance. In all recording sites, we performed five blows to obtain good quality seismic records.

3.2 Horizontal-Vertical Spectral Ratio (HVSR) and Soil Fundamental Period (T_S)

The HVSR (Nakamura 1989) is a low-cost and straightforward method to estimate the resonance frequency (F_S) and the fundamental period of soils (T_S), and therefore, it has been widely used for site effect studies in the last decade. The T_S peak reflects the primary resonance frequency and maximum amplification of the sediments. In this way, the T_S parameter is important because when it is close to the fundamental frequency of structures, resonance phenomena could be generated, causing severe damage or collapse. For civil engineering design and this paper's purposes, the T_S parameter is used to assess soil–structure resonance danger.

We chose the same MASW recording sites (Fig. 1); however we only recorded high quality microtremor data to perform the HVSR analysis in 47 locations (Table 2). The seismic records were performed using three components seismometer LE-2Dlite MkIII from Lennartz electronics GmbH and Obsidian digitizers from Kinometrics. The LE-2Dlite seismometer has eigenperiod of one seconds and upper frequency limit 100 Hz. The seismic sensor was deployed in each recording site and recorded seismic noise during 60 minutes. The seismic noise records were processed using the program GEOPSY 2.9.0 framework and main tools H/V and array processing (Wathelet et al. 2020). According with process spectral ratio was estimated through the division of two horizontal components between vertical. Criteria to determine the size of windows considered that at least 30 periods must be present in the spectra according with frequency considered. Fig. 4 shows an example of the 60 minutes seismic noise recorded with orthogonal channels and the estimated horizontal to vertical spectral ratio at location CONV.

3.3 Standard Penetration Test (SPT)

The Standard Penetration Test (SPT) is a procedure used in the geotechnical investigation to determine the relative density, angle of shearing resistance, and the strength of stiff soils. The SPT consists of drill a borehole to the desired sampling depth using a drill rod with a split-spoon sampler. That basic idea is driving the sampler into the ground using a hammer dropping from a specific height; then, the required blows to penetrate a specific depth are known as the standard penetration resistance (SPT_N). The results, with several corrections, are used to estimate the geotechnical engineering properties of the soil. The split-spoon sampler allows collecting soil samples to classify them according to a specific standard.

To inquire about the soil's geotechnical properties, we analyzed approximately 40 soil mechanics studies reports performed by private soil laboratories and provided by Civil Protection. However, in this study, we show six representative standard penetration tests perform within the study area (Fig. 1). Fig. 5 shows plots of the standard penetration resistance (SPT_N) and soil composition against depth. The SPT tests show that distinct sand, gravel, and clay combinations constitute the subsoil. The test SPT_{N-1} and SPT_{N-3} show soil with predominant contents of well-graded sands with little fines (SW) and silty sands (SM), and to less extent, poorly graded gravelly sands (SP). This soil composition is consistent with their location near the coast shore at the north of the city. On the other hand, the test SPT_{N-2} that is located within an estuary area shows soil with inorganic silts and clay composition (ML and CL). Finally, test SPT_{N-4} and SPT_{N-6} show soils with mixtures of well-graded gravels with different sand contents (GW and GS).

3.3 Structures classification and Fundamental Periods

Considering local design and construction practices in Puerto Vallarta city we decided to adopt building typology based on construction method and story number. We identify four typologies based on the construction materials and structural system:

Typology 1: Unreinforced and confined masonry houses of one to two stories without a proper seismic design or auto-constructed, and Adobe houses (6a).

Typology 2: Confined masonry houses of one to two stories with seismic design and constructed by an architect or a civil engineer following the construction/seismic codes and other regulations (6b).

Typology 3: Reinforce concrete (RC) buildings of moment resisting frames (MRF) and different combinations as infill masonry panels or braces (6c).

Typology 4: Steel MRF buildings and different combinations as infill masonry panels or braces (6d).

According to the currently existing buildings in Puerto Vallarta, we proposed a three groups classification based on the building height:

Goup 1: Low-rise buildings (height of 3-6 m), with one to two stories and a maximum height of six meters.

Goup 2: Mid-rise buildings (height of 9-18 m), with three to six stories and a maximum height of 18 meters.

Goup 3: High-rise buildings (21-36 m), with seven to twelve stories and a maximum height of 36 meters.

To estimate the fundamental structural period, T_E , of the buildings identified in Puerto Vallarta, we implemented two empirical relations related to the building typology. For typologies one (Fig. 6a) and two (Fig. 6b), we implement a relation initially proposed by UBC (1997) for shear wall buildings and later used in EUROCODE 8 (2004),

$$T_E = 0.05H^{0.75} \quad (2)$$

where H represents the total height of the building. For typologies three (Fig. 6c) and four (Fig. 6d), we implement a relation proposed by Housner and Brady (1963):

$$T_E = 0.05H^{0.75} \quad (2)$$

where N is the number of stories. Equation 3 is valid for a maximum number of stories N of 12 with a maximum height of three meters (total height of buildings of 36 meters). Initially, Housner and Brady (1963) proposed Equation 3 to estimate the fundamental period of MRF structures/buildings as a linear correlation with the number of stories. According to Salameh et al. (2016), this expression is used in most seismic codes in the U.S.A. for steel and RC framed structures. Therefore, Equation 3 is only useful to estimate the structural fundamental period T_E of typologies three and four.

4. Results

We performed a seismic vulnerability assessment of Puerto Vallarta using V_{S30} and HVSR-Ts geophysical microzonation, geotechnical data, and building structures analysis. The geophysical parameters were estimated at approximately 52 sites located within the city (Fig. 1). We recorded seismic data at each site with linear arrays of 24 vertical geophones and 60 minutes three orthogonal channels of seismic noise for V_S and HVSR estimations, respectively. We further constructed the V_{S30} soil classification (Fig. 7) and the Ts iso-period (Fig. 8) maps. Then we used the maps to estimate the resonant vulnerability for different types of structures and different heights.

Figure 7 shows that according to the V_{S30} parameter and the NEHRP soil classification (Table 1), the city of Puerto Vallarta has three soils, i.e., C, D, and E. We found a progressive transition from type C soil at the northwest area to soil type E towards the east and soil type C at the southeast. The study shows the lack of type A and B soils in Puerto Vallarta.

According to the parameter T_s (Fig. 8), we divided the city of Puerto Vallarta into four zones. Zone 1, with the lowest T_s values ranging between 0.13 and 0.46 seconds, blue areas. Zone 2, low-intermediated T_s values ranging between 0.46 and 0.83 seconds, green areas. Zone 2 mostly appears scattered with zone 3. Zone 3, high-intermediate T_s values ranging between 0.83 and 1.21 seconds, yellow areas. Zone 3 covers most of the city, extends from the center to the north and northeast. Zone 4, high T_s values ranging between 1.21 to 1.92 seconds, red and orange areas.

With the use of Equation 2 for typologies one and two (Fig. 6a,b), it is estimated a fundamental period T_E of 0.114 seconds for one story houses and 0.192 seconds in case of two story with a story height of 3 m and 6 m respectively. Considering the four typologies of Equation 3, the structural fundamental periods for group 1 ranges from 0.1 to 0.2 seconds, for group 2 from 0.3 to 0.6 seconds and in the case of high-rise buildings of group 3 from 0.7 to 1.2 seconds. It is worth noting that the structural fundamental periods obtained with Equation 2 are in agreement with the ones obtained with Equation 3. Thus, and for practical reasons, the fundamental periods of the buildings under consideration for this study are into the range of 0.1 to 1.2 seconds.

5. Discussion

The estimated V_{S30} values, and therefore the NEHRP soil classification (Fig. 7), correlate with the geology and geomorphology of the area (Fig. 2a). The highest V_{S30} values were estimated for sites located at the southern and southeastern region of the city, near the mountains with hard soils, i.e., riolythic tuff material (KsTpsTR). The central and northeast region has class D soil with V_{S30} ranging between 180 to 360 m/s that correlates with alluvial (Qal) materials representing the entire sedimentary roof deposited over the basin over time. Finally, the northwest of the city has class E soil with V_{S30} values less than 180 m/s (Fig. 7) and Gleysol (Gl) soil. While the SPT shows principally well and poorly graded sands, and in less content silty sands, silts and clays. The soil characteristics and the shallow water table in this area must be analyzed to determine the possible occurrence of liquefaction.

The estimated T_s values (Fig. 8) correlate with the geology, soil classification (Fig. 2) and the V_{S30} parameter (Fig. 7). Zone 1, identified in the map with blue color (Fig. 8), covers the city's southeast near the mountain area with shallow and outcropping rocks. Fig. 8 shows that zone 1 correlates with the riolythic tuff region material (Fig. 2b) and V_{S30} soil class C (Fig. 7). The riolythic tuff considered consolidated volcanic rock is expected to have low T_s values, in agreement with those in Fig. 8 that range between 0.13 and 0.46 seconds in this area. Zone 3 identified in the map with yellow color, covers most of the studied area and correlates with alluvial (Qal) materials (Fig. 2b) and V_{S30} soil class D and E (Fig. 7). Although there are not enough SPT to have a detailed map, the SPT_{N-1} to SPT_{N-5} that are located within this area shows distinct sand, gravel, and clay combinations that constitute in situ measurements that corroborate the composition of this kind of subsoil. It is worth notice that most urban area of Puerto Vallarta city is located on this alluvial deposits. With particular interest, around the estuary El Salado, at the northwest part of the area (Fig. 2a) overlaps with Gleysol (Gl) soil type and the lowest V_{S30} values of

the study area with soil class E. Characteristic of having a shallow phreatic zone, in addition to being soils prone to flooding. Finally Zone 4 identified in the map with red and orange colors, is located in two zones within the studied area, one at the northern part of the city and the other at the east. The recording sites that produce the T_S values of zone 4 were located in mountain regions with polytmic conglomerate (TmCgo), but with different geomorphology characteristics that lead to different soil type. At the southeast there is an area of high erosion, i.e. rivers, with Regosol soil while the northwest region has Fluvisol (Fig. 2a), which are typical of the surrounding rivers, so they are usually very clayey.

It is well known that the site response is intrinsically linked to structural design. For this reason, we compare the V_{S30} and the T_S geotechnical zonation of Puerto Vallarta with the construction typology and the fundamental structural period, T_E of buildings within the city. Fig. 9 shows the building classification superimposed on V_{S30} and T_S values. The tourist area of Puerto Vallarta mainly located along the shore is highlighted in Fig. 9 by the red line polygon. Within this area we identified three subzones based on the T_S , i.e., the first with T_S of 0.13-0.46 seconds occupying 38%, the second with T_S of 0.83-1.21 seconds the 60% and the third with periods ranging from 0.46 to 0.83 seconds 2% of the total tourist area. While the rest of the city, i.e., the residential/commercial area, where most of the housing, infrastructure such as schools, hospitals, as well as offices are located. It has dominating soil period corresponds between 0.83 and 1.21 seconds and followed by a very soft soil 1.21-1.92 seconds. Furthermore, some other parts of minor area are also identified with soil periods of about 0.13-0.83 seconds.

In the structural dynamics field, the coupling between the fundamental structural period, T_E , and the fundamental period of soil, T_S , generates the resonance phenomenon at the base of the building and its structure. The dynamic seismic amplification may lead to collapses in brittle structures and intermediate to considerable damage with a high probability of collapse/permanent drifts in MRF structures and other buildings (e.g. Preciado et al. 2020ab; Ramirez-Gaytan et al. 2020). In this way, by comparing the T_E and the T_S parameters, we can infer areas vulnerable to intermediate/severe damage or collapse by resonance effects in case of an intermediate or high-intensity earthquake. (1) Scattered over the city, Typology 1 (Fig. 6a) adobe and poorly confined masonry houses of one to two stories. (2) Within the tourist area (T_S values between 0.13 and 1.21 seconds), typology 2 (Fig. 6b), confined masonry buildings with one to five stories (T_E values between 0.1 and 0.5 seconds) and typology 3 and 4 (Fig. 6cd), RC and MRF of steel buildings with one to twelve stories (T_E values between 0.1 and 1.2 seconds). (3) Within residential/commercial areas, at the small-identified areas with T_S values between 0.13 and 0.83 seconds, typology 3 (Fig. 6c), especially confined masonry buildings of one to five stories (T_E values between 0.1 and 0.5 seconds). (4) Within the residential/commercial areas, in the area of very soft soil conditions (T_S values between 1.21 and 1.92 seconds), typology 4 (Fig. 6d), MRF buildings of one to 12 stories (T_E values between 0.13 and 1.21 seconds). It is worth noticing that within the residential/commercial areas, there are no intermediate or high-rise buildings; the authors of this paper recommend no to construct tall buildings in this area.

6. Conclusions

- Based on V_{S30} values, Puerto Vallarta has three soil types, i.e., C, D, and E. The city's central area has type E and D soil, while the south near the mountains has type C soil. Puerto Vallarta has no type A and B soils, according to the study.
- Based on the T_S values, we proposed a geotechnical microzonation for Puerto Vallarta consisting of four zones. Zone 1 shows the lowest T_S , between 0.13 and 0.46 seconds. Zone 2 shows T_S ranging from 0.46 to 0.83 seconds mostly appears incrustated and scattered into zone 3. Zone 3 shows intermediate T_S (0.83 to 1.21 seconds) covering the largest area within the city, extends from the center to north and northeast. Zone 4 shows the longest T_S ranging between 1.21 to 1.92 seconds.
- Both, T_S and V_{S30} parameter maps (7 and 8) show good fit with edaphology and lithology maps (Fig. 2)
- According to the building inventory of Puerto Vallarta, we defined four main typologies in construction materials and structural systems. The typologies were ranging from auto-constructed houses of adobe and poorly confined masonry to seismically designed confined houses and MRF with structural periods for all buildings between 0.1 and 1.2 seconds.
- The vulnerability of the buildings, was inferred from the coupling between the structural fundamental period T_E and the soil period T_S . Most of the confined masonry buildings from one to five stories and MRF buildings of one to 12 stories are highly vulnerable to the resonance phenomenon.
- The residential/commercial area has vulnerable adobe and poorly confined masonry houses of one to two stories, confined masonry of one to five stories and low, intermediate and high-rise MRF buildings. In the very soft soil conditions area (T_S between 1.21 and 1.92 seconds), it is recommended not to construct tall buildings in order to prevent the dynamic amplification by the resonance effect.
- The high-rise buildings in the tourist area exceeding 12 stories are no analyzed due to the limitations of the empirical equations. In that case, we recommend constructing the 3D models of typical high-rise buildings to estimate their fundamental period.
- The T_E is limited by the original assumption of the developer of the empirical relations; therefore it is necessary to perform a comprehensive instrumentation of buildings within Puerto Vallarta.
- Further microzonation analysis using a more sophisticate methodology like multicriteria analysis.
- The data and results sharing between local authorities and the scientific community increment the level of collaboration between the different actors that should collaborate towards the risk mitigation.

Declarations

Acknowledgments

This research is part of the work program of the CA “CIENCIAS DE LA TIERRA – PELIGROS NATURALES” number UDG-CA-941. Karen L. Flores was supported by CONACYT-PNPC scholarship. We specially thank Coordinación Municipal de Protección Civil y Bomberos, Puerto Vallarta, Jalisco for their unconditional support in the logistics and data sharing.

Founding

This research was in part founded by the research project “Evaluación de la Vulnerabilidad Sísmica en Puerto Vallarta” from the CA strengthening program from PRODEP (IDCA: 28289; CLAVE: UDG-CA-941). This research was in part founded by the Coordinación Municipal de Protección Civil y Bomberos, Puerto Vallarta, Jalisco.

Conflict of interest

The authors declare that they have no conflict of interest.

References

- Allan JF (1986) Geology of the Northern Colima and Zacoalco Grabens, southwest Mexico: Late Cenozoic rifting in the Mexican Volcanic Belt. *Geol Soc America*. [https://doi.org/10.1130/0016-7606\(1986\)97<473:GOTNCA>2.0.CO;2](https://doi.org/10.1130/0016-7606(1986)97<473:GOTNCA>2.0.CO;2)
- Arzate JA, Alvarez R, Yutsis V, Pacheco J, López-Loera H (2006) Geophysical modeling of Valle de Banderas graben and its structural relation to Bahía de Banderas, Mexico. *Revista Mexicana de Ciencias Geológicas*. 23:184–198.
- Bandy W, Mortera-Gutierrez C, Urrutia-Fucuguachi J, Hilde TWC (1995) The subducted Rivera-Cocos plate boundary: Where is it, what is it, and what is its relationship to the Colima rift? *Geophys. Res. Lett.* 22:3075–3078.
- Borcherdt R (1994) Estimates of site-dependent response spectra for design (methodology and justification). *Earthquake Spectra*. 10:617–654.
- Borcherdt R (1992) Simplified site classes and empirical amplification factors for site-dependent code provisions. NCEER, SEAOC, BSSC workshop on site response during earthquakes and seismic code provisions, University of Southern California. 1–33.
- Borcherdt RD (2012) VS30 – A site-characterization parameter for use in building codes, simplified earthquake resistant design, GMPES, and shakemaps. 15 World Conference of Earthquake Engineering Lisboa. 1–10.
- BSSC (2009) NEHRP recommended provisions for seismic regulations for new buildings and other structures. Part1: provisions (FEMA368). Federal Emergency Management Agency, Washington, DC.

- Courboux F, Singh SK, Pacheco JF, Ammon CJ (1997) The 1995 Colima-Jalisco, Mexico, earthquake (Mw 8): A study of the rupture process. *Geophys. Res. Lett.* 24:1019–1022.
- DeMets C, Traylen S (2000) Motion of the Rivera plate since 10 Ma relative to the Pacific and North American plates and the mantle. *Tectonophysics*. [https://doi.org/10.1016/S0040-1951\(99\)00309-1](https://doi.org/10.1016/S0040-1951(99)00309-1)
- EUROCODE 8, 2004. Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings. European Standard, European Union.
- Gutierrez QJ, Escudero CR, Núñez-Cornu FJ (2015) Geometry of the Rivera–Cocos Subduction Zone Inferred from Local Seismicity. *Bull. Seism. Soc. Am.* <https://doi.org/10.1785/0120140358>
- Housner G, Brady A (1963) Natural Periods of Vibration of Buildings. *Journal of Engineering Mechanics*. <https://doi.org/10.1061/JMCEA3.0000404>
- INEGI, 2021. Instituto Nacional de Estadística y Geografía (INEGI). Aguascalientes, México. <http://www.inegi.org.mx>
- IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, Update 2015. World Soil Resources Reports 106, FAO, Rome.
- Johnson CA, Harrison CGA (1990) Neotectonics in central Mexico. *Physics of the Earth and Planetary Interiors*. [https://doi.org/10.1016/0031-9201\(90\)90037-X](https://doi.org/10.1016/0031-9201(90)90037-X)
- Kelleher J, Sykes L, Oliver J (1973) Possible criteria for predicting earthquake locations and their application to major plate boundaries of the Pacific and the Caribbean. *J. Geophys. Res.* doi:10.1029/JB078i014p02547
- Luhr JF, Nelson SA, Allan JF, Carmichael ISE (1985) Active rifting in southwestern Mexico: Manifestations of an incipient eastward spreading-ridge jump. *Geology*. [https://doi.org/10.1130/0091-7613\(1985\)13<54:ARISMM>2.0.CO;2](https://doi.org/10.1130/0091-7613(1985)13<54:ARISMM>2.0.CO;2)
- Nakamura Y (1989) A Method for Dynamic Characteristics Estimation of Subsurface using Microtremor on the Ground Source. *Railway Technical Research Institute*. 30:25–33.
- Park CB, Miller RD, Xia J (1999) Multichannel analysis of surface waves. *Geophysics*. 64:800–808.
- Park CB, Miller RD, Xia J, Ivanov J (2007) Multichannel analysis of surface waves (MASW)—active and passive methods. *The Leading Edge*. 26:60–64.
- Preciado A, Santos JC, Silva C, Ramirez-Gaytan A, Falcon JM (2020a) Seismic damage and retrofitting identification in unreinforced masonry Churches and bell towers by the September 19, 2017 (Mw= 7.1) Puebla-Morelos Earthquake. *Engineering Failure Analysis*. <https://doi.org/10.1016/j.engfailanal.2020.104924>

Preciado A, Ramirez-Gaytan A, Santos JC, Rodriguez O (2020b) Seismic vulnerability assessment and reduction at a territorial scale on masonry and adobe housing by rapid vulnerability indicators: the case of Tlajomulco, Mexico. *International Journal of Disaster Risk Reduction*.
<https://doi.org/10.1016/j.ijdr.2019.101425>

Ramirez-Gaytan A, Flores-Estrella H, Preciado A, Bandy WL, Lazcano S, Alcantara-Nolasco L, Aguirre-Gonzalez J, Korn M (2020) Subsoil classification and geotechnical zonation for Guadalajara City, México: Vs30, soil fundamental periods, 3D structure and profiles. *Near Surface Geophysics*.
<https://doi.org/10.1002/nsg.12085>

Salameh C, Guillier B, Harb J, Cornou C, Bard PY, Voisin C, Mariscal A (2021) Seismic response of Beirut (Lebanon) buildings: instrumental results from ambient vibrations. *Bulletin of Earthquake Engineering*.
<https://doi.org/10.1007/s10518-016-9920-9>

Singh SK, Astiz L, Havskov J (1981) Seismic Gaps and Recurrence Periods of Large Earthquakes along the Mexican Subduction Zone: A Reexamination. *Bull. Seism. Soc. Am.* 71:827–843.

Singh SK, Yamamoto J, Havskov J, Guzmán M, Novelo D, Castro R (1980) Seismic gap of Michoacan, Mexico. *Geophys. Res. Lett.* <https://doi.org/10.1029/GL007i001p00069>

Stock JM, Lee J (1994) Do microplates in subduction zones leave a geological record? *Tectonics*.
<https://doi.org/10.1029/94TC01808>

UBC (1997) Uniform Building Code. International conference of building officials. Whittier, California, USA.

Wathelet M, Chatelain JL, Cornou C, Di Giulio G, Guillier B, Ohrnberger M, Savvaidis A (2020) A User-Friendly Open-Source Tool Set for Ambient Vibration Processing. *Seismological Research Letters*.
<https://doi.org/10.1785/0220190360>.

Tables

Table 1. NEHRP Soil profile type classifications for seismic amplifications (BSSC, 2003)		
Soil type NEHRP	General description	Average shear wave velocity to 30 meters depth (m/s)
A	Hard rock	$V_{s30} > 1500$
B	Rock	$760 \text{ m/s} < V_{s30} < 1500$
C	Very dense soil and soft rock	$360 \text{ m/s} < V_{s30} < 760$
D	Stiff soil $15 < \text{SPT}_N < 50$ or $50 > 100 \text{ kPa}$	$180 \text{ m/s} < V_{s30} < 360$
E	Soil or any profile with more than 3 m of soft clay defined as soil with $\text{PI} > 20$, $w > 40\%$, and $S_u < \text{kPa}$	$V_{s30} < 180$
F	Soils requiring site-specific evaluations	
Standard penetration resistance (SPT_N), Undrained shear strength (S_u), Plasticity index (PI), water content (w)		

Table 1. List of the 52 sites under study in Puerto Vallarta.						
	Name	LATITUD	LONGITUD	Vs30 (m/s)	Ts (sec)	Heigth
1	5DIC	20.61735	-105.2326	381	0.29	1 – 6
2	BOCA	20.67204	-105.2749	156	0.31	1 – 6
3	CAÑA	20.69514	-105.2086	216	0.23	1 – 6
4	CHNA	20.58820	-105.2433	420	0.13	7 – 13
5	CLRD	20.76841	-105.1548	221	0.92	1 – 6
6	CLVA	20.66113	-105.2166	304	0.99	1 – 6
7	CNTN	20.73548	-105.1851	345	1.72	1 – 6
8	CONV	20.68027	-105.2326	188	0.74	1 – 6
9	ECOT	20.75106	-105.1643	248	1.98	1 – 6
10	EMZP	20.60606	-105.2310	417	0.29	1 – 6
11	GAST	20.61068	-105.2244	644	0.20	1 – 6
12	GDVI	20.67760	-105.2412	132	0.97	1 – 6
13	HERM	20.66001	-105.1898	521	1.93	1 – 6
14	JRDN	20.63757	-105.2182	251	0.61	1 – 6
15	JUNT	20.70243	-105.2418	159	0.88	1 – 6
16	LACA	20.62509	-105.2275	194	1.54	14 – 20
17	LCAL	20.66010	-105.2047	403	0.16	1 – 6
18	LLAN	20.70820	-105.2033	390	0.67	1 – 6
19	LVOC	20.63711	-105.2026	373	1.82	1 – 6
20	MAVA	20.67076	-105.2583	183	1.04	7 – 13
21	MOJO	20.69425	-105.2253	188	-	1 – 6
22	NGAL	20.56160	-105.2424	632	0.08	1 – 6
23	NIXT	20.72026	-105.2326	249	0.88	1 – 6
24	NVHO	20.69467	-105.2960	209	-	1 – 6
25	ORDZ	20.63898	-105.2273	195	0.80	1 – 6
26	PALM	20.67483	-105.1878	382	0.98	1 – 6
27	PAPA	20.68215	-105.2269	182	-	1 – 6

28	PARA	20.65186	-105.2396	159	0.94	21 – 25
29	PAUN	20.70335	-105.2188	175	1.93	1 – 6
30	PSAN	20.59042	-105.2129	404	1.16	1 – 6
31	PUNI	20.67828	-105.2165	305	-	1 – 6
32	RAMB	20.62791	-105.2055	455	1.92	1 – 6
33	RIPU	20.67897	-105.2371	141	3.13	1 – 6
34	RMAC	20.60202	-105.2274	475	0.21	1 – 6
35	RNCH	20.73521	-105.1509	199	0.91	1 – 6
36	SADO	20.71967	-105.1969	329	1.87	1 – 6
37	SALI	20.67419	-105.1972	331	0.98	1 – 6
38	SEST	20.64803	-105.1956	382	1.82	1 – 6
39	SNMA	20.62827	-105.2201	288	0.20	1 – 6
40	TABA	20.65183	-105.2338	145	0.94	7 – 13
41	TPPV	20.69190	-105.2569	209	0.79	1 – 6
42	UIXT	20.71829	-105.2085	360	1.87	1 – 6
43	V750	20.65179	-105.2303	148	0.85	7 – 13
44	VAVI	20.64877	-105.2202	273	1.12	1 – 6
45	VGPE	20.64689	-105.2060	293	1.93	1 – 6
46	VIFL	20.67517	-105.2488	159	1.01	7 – 13
47	VIVA	20.68370	-105.1809	530	0.91	1 – 6
48	VIVE	20.68940	-105.1973	365	0.59	1 – 6
49	VIXT	20.71528	-105.2166	247	1.93	1 – 6
50	VMAR	20.66318	-105.2322	147	0.79	1 – 6
51	VOLC	20.67520	-105.1835	422	1.52	1 – 6
52	VUNI	20.69973	-105.2250	289	-	1 – 6

Figures

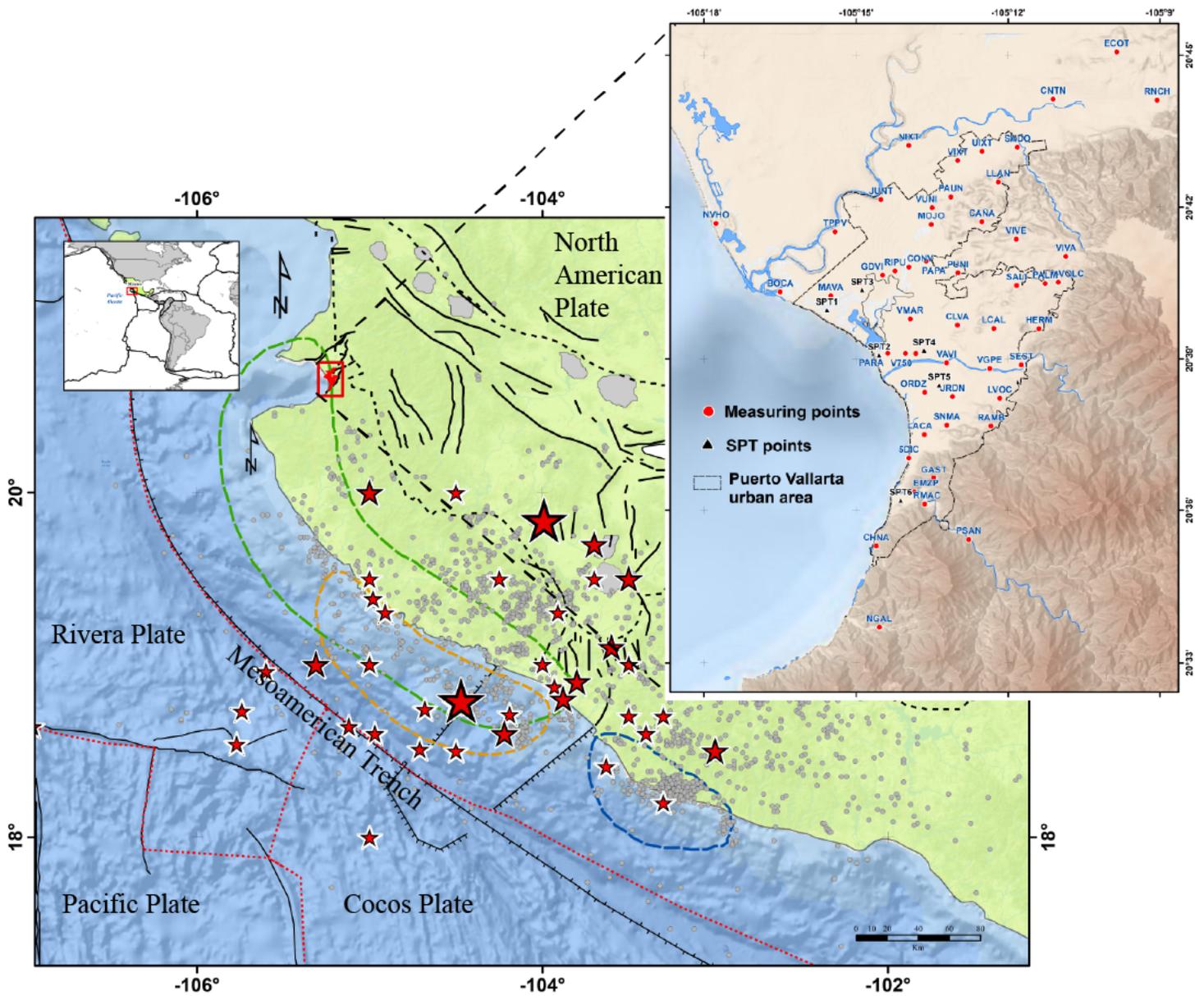


Figure 1

Map a) shows the main tectonic units within Western Mexico include the Pacific Plate and North American Plates, the Rivera Plate, the Cocos Plate, and the Jalisco Block (JB). Main tectonic structures are the Mesoamerican trench, the Tepic–Zacoalco rift (TZR), Colima rifts (CR), Armería Canyon (AC), and El Gordo graben (GG). Historic seismicity e.g., the 8.2 magnitude 1932 earthquakes (green line; Singh et al. 1980), 7.6 magnitude earthquake 1973 (blue line; Singh et al. 1981) and the 8.0 magnitude 1995 earthquakes (yellow line; Courbulex et al. 1997). Gray dots show local seismicity from 2006 to 2007 (Gutierrez et al. 2015). Major late Miocene to present volcanism (gray areas). Inset shows the location of the study region. Figure modified from DeMets and Traylen (2000). Map b) shows Puerto Vallarta city with seismic data measured and SPT locations. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area o bbnhjr of its

authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

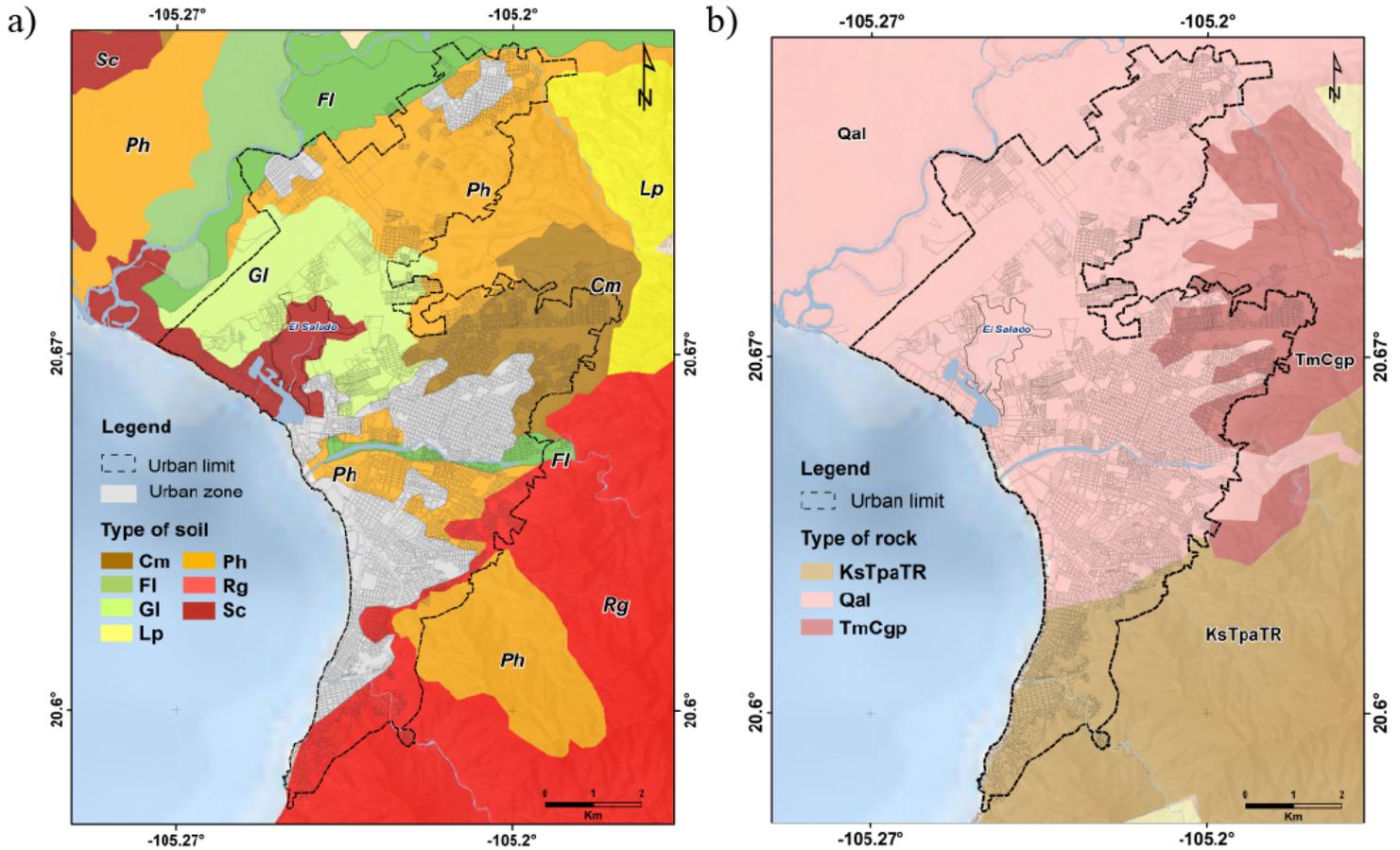


Figure 2

Map a) shows edaphology and map b) shows lithology of the study zone (INEGI 2021). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or bbnhjr of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

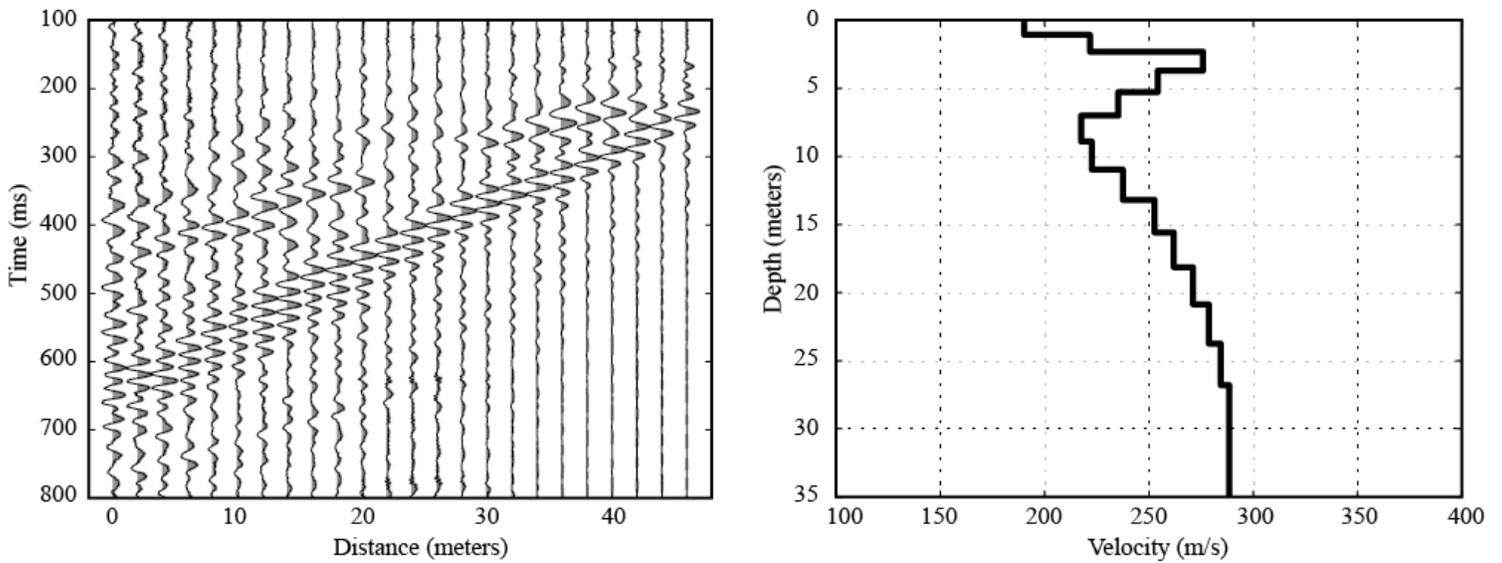


Figure 3

Example of the data recorded with 24 vertical geophones (left) and the estimated velocity profile at location COPV.

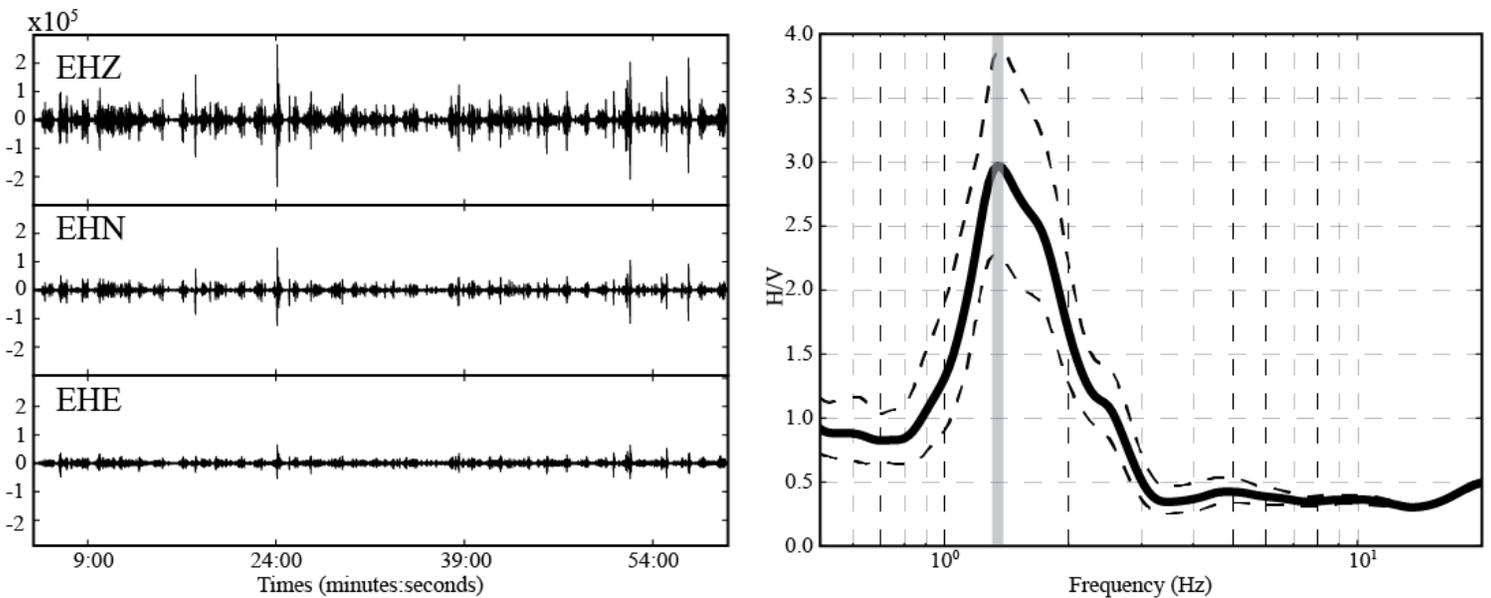


Figure 4

Example of the 60 minutes seismic noise recorded with orthogonal channels (left) and the estimated horizontal to vertical spectral ratio (right) at location CONV.

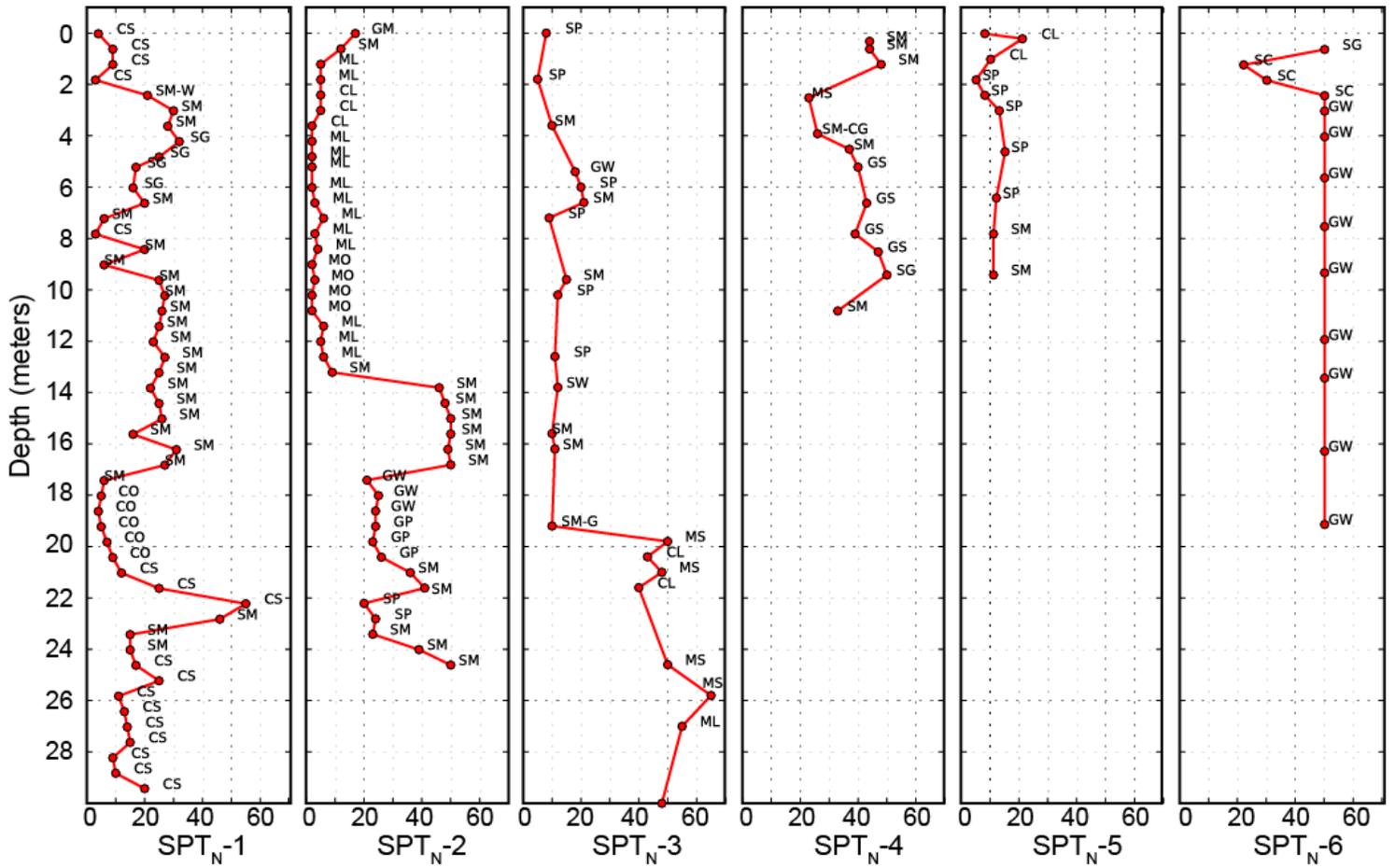


Figure 5

Standard penetration resistance, SPT_N, versus depth and soil classification according to Standard Penetration Test performed at six-selected location within Puerto Vallarta city. Gravels (G) well-graded (W), poorly graded (P), sandy (S). Sands (S), plasticity limits above “A” line p.I. > 4 < 7 (M) and (C), with gravels (G). Silts (M) and Clays (C).



Figure 6

Buildings Classification in Puerto Vallarta. a) typology 1 auto-constructed houses; b) typology 2 confined masonry with seismic design; c) typology 3 RC MRF and d) typology 4 steel MRF.

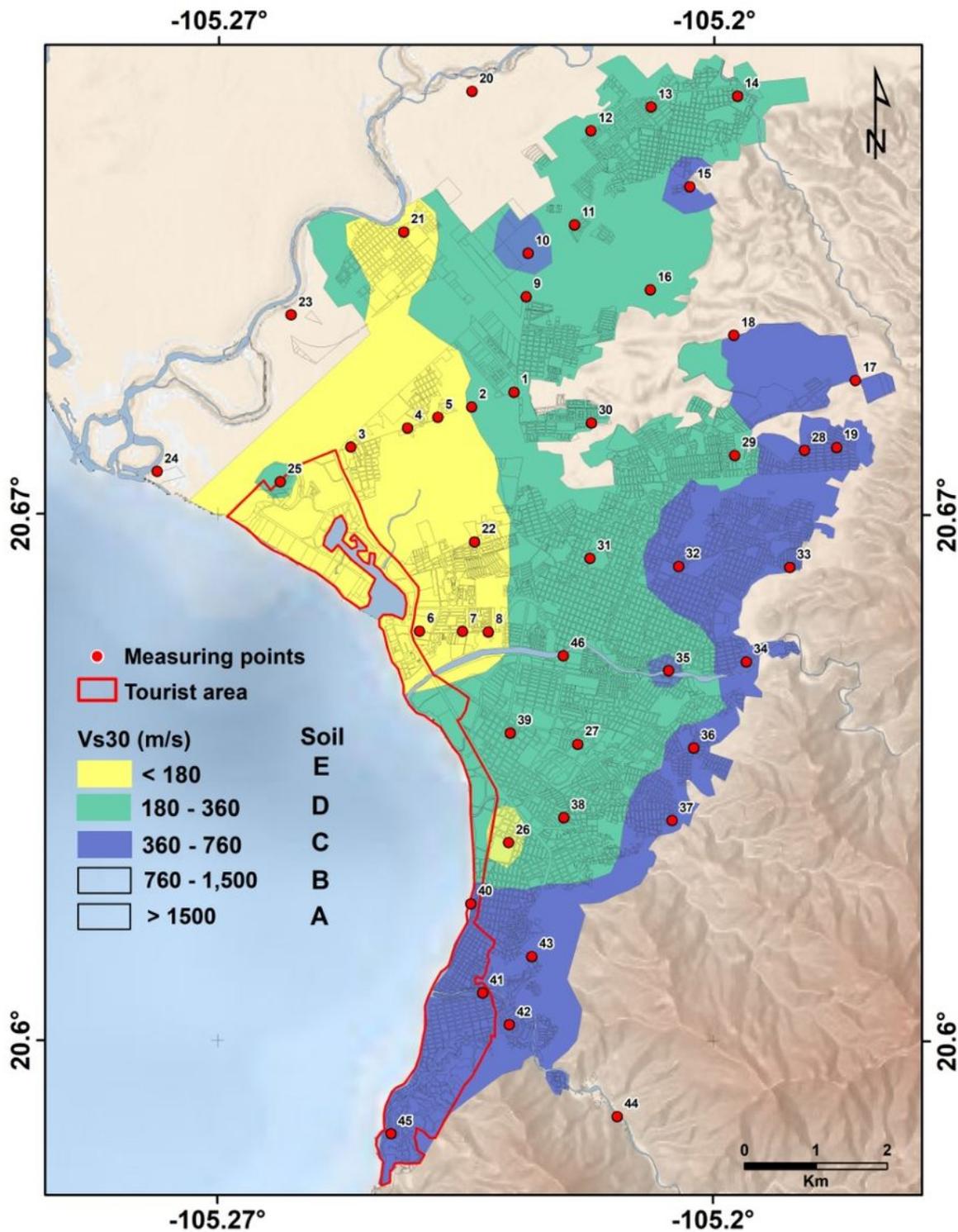


Figure 7

VS30 interpolations map for the 55 sites with in Puerto Vallarta and site classification according with NEHRP (BSSC, 2009). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area o bbnhjr of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

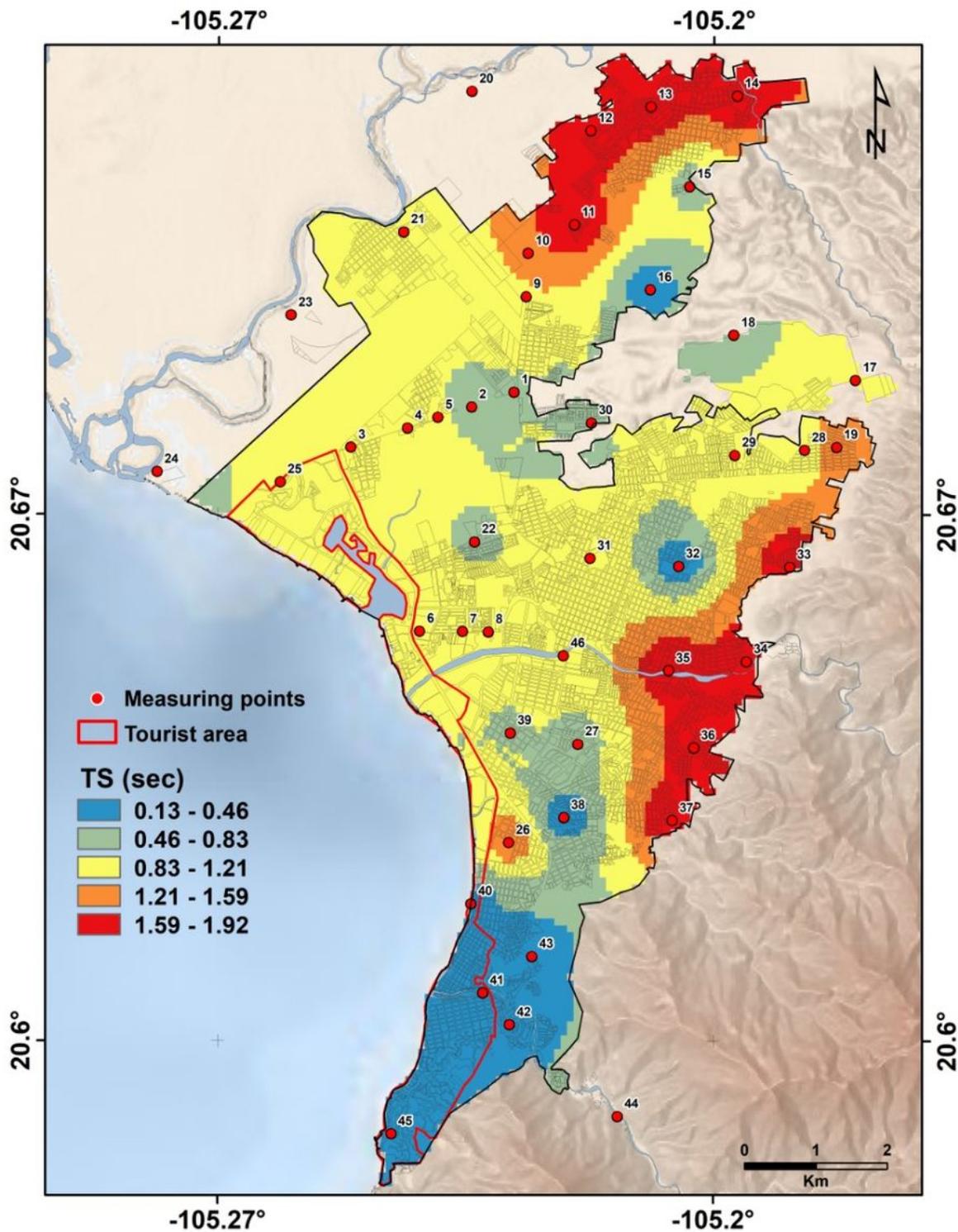


Figure 8

Ts interpolation map for the 33 sites under study in Puerto Vallarta. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

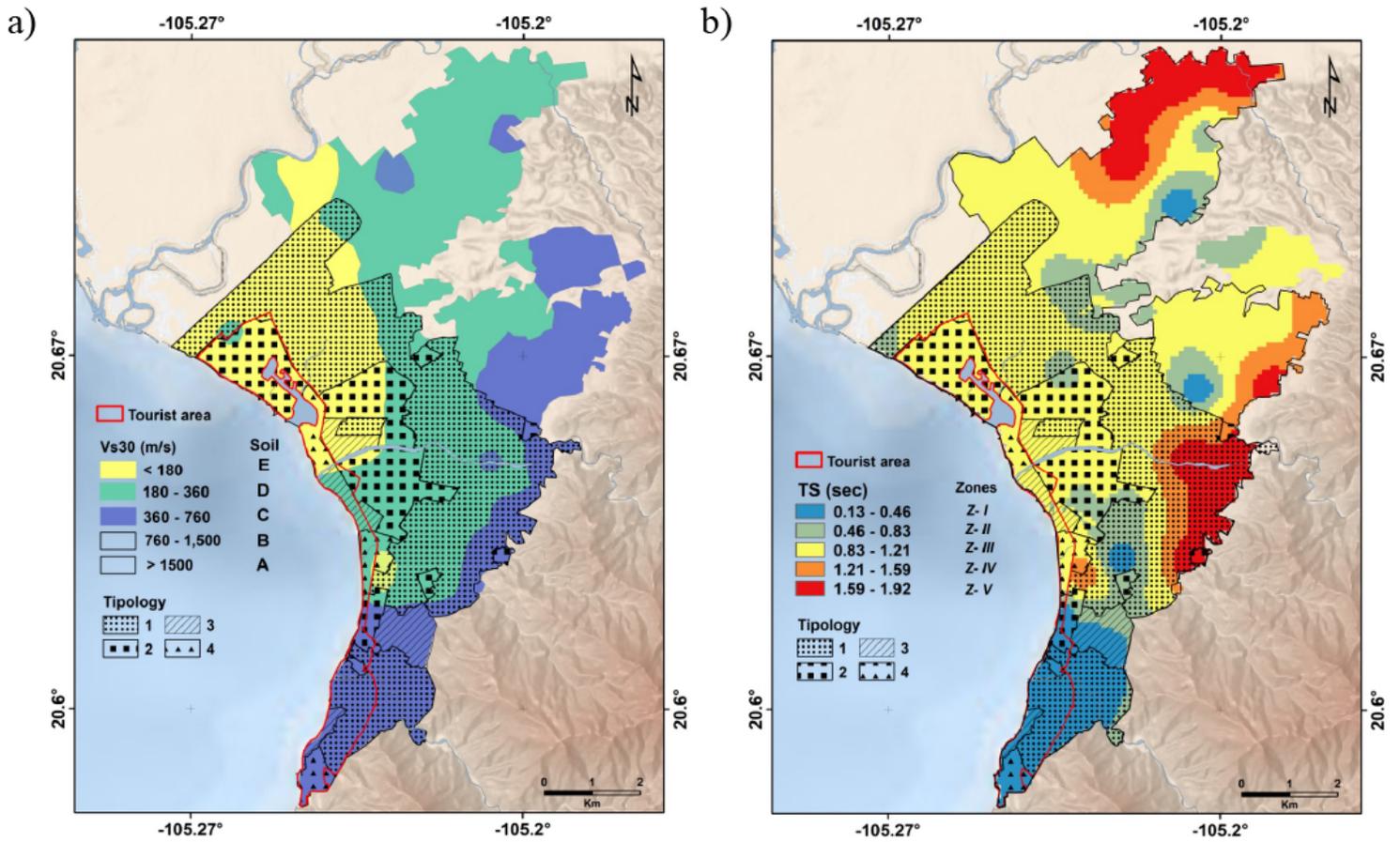


Figure 9

a) Comparison of Vs30 versus structural systems and b) comparison of Ts versus structural systems. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.