Training and Communication for Earthquake Risk Assessment

TREQ Project

PSHA models and datasets for urban hazard assessment

Deliverable 2.2.1 – Version 1.0.0

Global Earthquake Model (GEM) Foundation

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Description of selected PSHA models and compiled datasets for urban hazard assessment

PSHA models and datasets for urban hazard assessment

Deliverable D2.2.1

Technical report produced in the context of the TREQ project

Version 1.0.0 – August, 2020

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Collaborators

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The TREQ Project is designed to demonstrate how earthquake hazard and risk assessment can inform decision makers in the development of risk reduction policies, as well as how earthquake risk can be properly communicated to stakeholders and the public in general. Specifically, the project aims to develop capacity for urban earthquake risk assessment in Latin America, Quito (Ecuador), Cali (Colombia), and Santiago de los Caballeros (Dominican Republic), while the second part will produce training, educational and communication materials that will enhance the understanding of earthquake risk worldwide. This program targets a wide spectrum of stakeholders, categorized into four main groups: governance (decision-makers/public authorities), industry (practitioners and professionals), academia (researchers and professors), and the community.

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1 INTRODUCTION

Latin America and Caribbean (LAC) is among the most disaster-prone developing regions in the world. In the last decade 25 percent of earthquakes with magnitude 8.0 or higher have occurred in South America, affecting 14 million people, with hundreds of thousands of injured and/or fatalities (i.e. 2010 Haiti earthquake with more than 300K of deaths ranks among the 10 deadliest events in human history, see Figure 1).

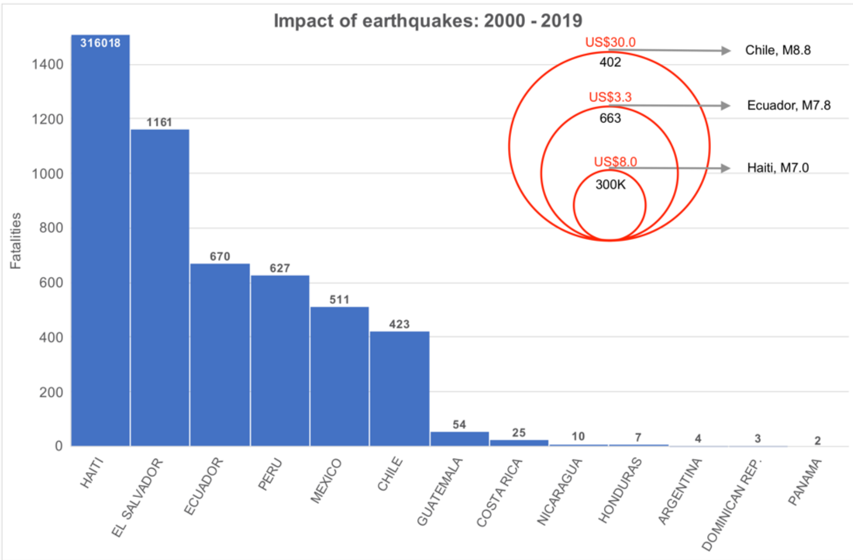


Figure 1. Earthquake fatalities in the last decade for the LAC region. The Haiti 2010 event accounts for 98% of total deaths in the whole region. Deaths and economic loses (in billions of US dollars) for three large events are present too. Source: the NOAA Significant Earthquake Database.

Earthquakes have critically affected the development effectiveness of the LAC countries, causing tremendous damages to the building environment and infrastructures. The Haiti event reduced Haiti's GDP by 5.1 percent, damaging more than 294K homes and destroying 106K of them. This catastrophic situation was exacerbated by the extreme vulnerability present in the country, the poverty, the lack of preparedness and response capacity of national authorities. This confirms that the earthquake impact largely depends on context.

In contrast to Haiti, other countries as Chile, with a modern and accurate building code, warning systems and regular evacuation simulations and people with an adequate culture of earthquake preparedness, large events have a limited impact in population (i.e. injured and fatalities), but still devastating damages to the building environment and infrastructure (i.e. 2010 Maule earthquake caused US$30 billion in economic losses).

The Ecuador 2016 event (M7.8, US$3.3 billion in economic losses and 663 deaths) demonstrated that there is still challenges and needs to overcome. For instance, EERI (2016) reported that losses were related with total or partial collapse of houses and important facilities as hospitals, schools, water and electric facilities, caused mainly by physical vulnerability of the infrastructure.

Given the existing needs and challenges in understanding the potential impact of large events in the LAC region, several initiatives have been performed by GEM in the last years (i.e., SARA, CCARA projects). The results from these initiatives globally harmonized in the GEM Global Seismic Hazard and Risk Maps (Global Earthquake Model, available at https://www.globalquakemodel.org/gem) confirmed that earthquake risk is on the rise and large events are expected to take an increasing number of lives. More work must be carried out to understand seismic hazard and earthquake risk and properly introduce and communicate this understanding to effectively reduce the risk.

The TREQ project (Training and Communication on Earthquake Risk Assessment), a collaborative project led by GEM and funded by the U.S. Agency for International Development (USAID-OFDA) intended to take actions in this direction working in three urban centres, selected as pilot cases (Quito, in Ecuador; Cali in Colombia and Santiago de los Caballeros in the Dominican Republic). In close collaboration with local stakeholders, detailed hazard and risk assessments for each city will be developed. These results could be directly used on disaster risk reduction strategies by local administrations and decision makers. Special emphasis will be given to strength local capacities and the application of the results and information generated in the framework of the TREQ project.

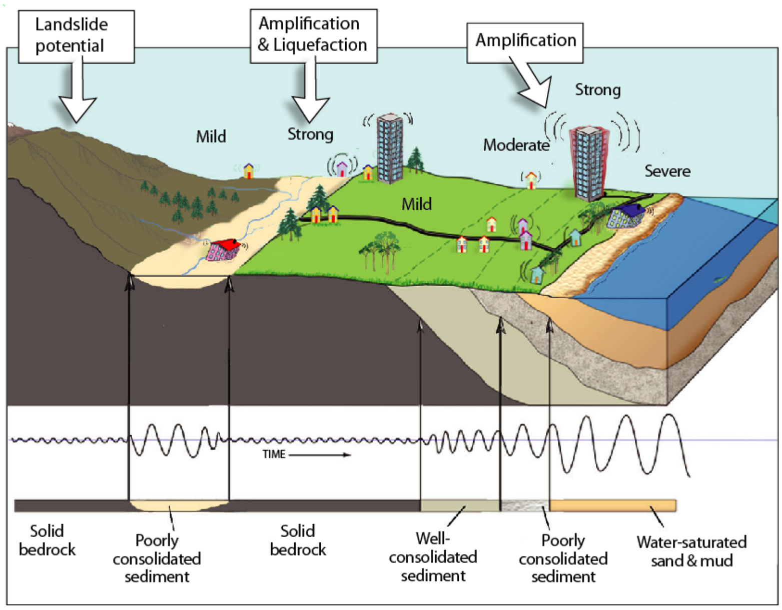


Figure 2. Earthquake effects at an urban scale. Source : https://serc.carleton.edu/205923.

The program is organized in two major parts: 1) seismic hazard and risk assessment at urban scale, and 2) improvement of training, educational and communication material.

Urban seismic hazard assessment must be built to evidence the earthquake effects - in terms of ground shaking, see Figure 2 – to a location (i.e. city, municipality, etc). Then, results from urban seismic hazard must include the effects of local geology, together with soils, which usually are not incorporated to national or regional seismic hazard results (i.e. maps, curves, uhs). In addition, the expected losses due to secondary perils induced by earthquakes impacting the cities must be considered. If possible, the hazard related with landslides and liquefaction phenomena triggered by seismic events must be included in the analysis. The selection of the methodologies to be used in TREQ will be based on the information made available by local collaborators and administrations involved.

Following these premises, in the next section of this report we describe the state-of-the-art of the seismic hazard modelling in the three countries involved, as well as the criteria used to select the best model available to compute ground shaking on reference bedrock for each city and a brief description of the sources affecting each city.

The third section is dedicated to the cities, in particular to: the information required to perform the urban seismic hazard at this level, the microzonation studies performed in the past for each city, what was the knowledge, data and results obtained and lastly, which information/data is available for each city, their format and spatial compliment.

2 SELECTION OF PROBABILISTIC SEISMIC HAZARD MODELS

2.1 Seismic hazard assessment

The major goal of the seismic hazard assessment (SHA) is to forecast future ground shaking caused by earthquake occurrence in a single site or region. The SHA results are then usually used as structural design guidelines or risk reduction strategies by decision making and local administrations.

In modern SHA, the probabilistic assessment (PSHA) is usually used for most national scale seismic hazard studies. The current PSHA modelling is a multidisciplinary process, which integrates several Earth-science fields as geology, active tectonic, seismology, geodesy, geophysics, and engineering seismology to scientifically envisage what we really know about earthquake occurrence and the ground shaking process. A modern PSHA model must include at least two components: seismic-source (SSM) and ground-motion models (GMM) and, being a probabilistic framework forecasting future ground shaking, uncertainty is an inherent element and must be considered. Then, we can include uncertainty (UNM) as a third component of the model (Gerstenberger et al. 2020).

In PSHA, the uncertainties are formally divided in two categories: aleatory and epistemic. The aleatory uncertainties describe the intrinsic irreducible variability of the process generating ground-shaking in a particular site, while the epistemic uncertainties account for our limited knowledge about the process itself. The epistemic uncertainty is a more controversial topic (Marzocchi et al., 2015; Bommer, 2003; Bommer and Scherbaum, 2008). However, the possibility to include multiple sources of uncertainty in the modelling and to propagate them through to the hazard results constitutes an important key of PSHA. The common manner of accounting for epistemic uncertainties is the “logic tree” approach (e.g. Kulkarni et al., 1984, Budnitz et al., 1997). In some cases (i.e. GEM models following OpenQuake standards), the epistemic uncertainties regarding SSM and GMM are treated independently.

The results provided by PSHA depend on the user needs and the resolution of the analysis (i.e. single site or regional assessment). At a national scale, a set of “classical” results can be obtained for each site and for each logic tree sample if epistemic uncertainties are considered in the computation (hazard curves, hazard maps and uniform hazard spectra or UHS). Statistical results (mean, standard deviation, quantiles) are commonly used to represent the average forecasting of the ground shaking for different probabilities of exceedances (poes) and/or intensity measure types (imts) and reference soil conditions (bedrock, soil [classes]). Additional outputs can be facilitated through a disaggregation analysis, which investigate the contribution of the SSM and the GMM to the probability of exceeding a certain ground motion level at a given site.

2.2 Criteria used to select the reference seismic hazard model

Due our major goal is to compute detailed hazard and risk assessment at urban scale, we focalize the review of available PSHA models at a national or sub-regional scale for the three selected cities. Despite the basic principles to build a national PSHA model (Cornell, 1968; McGuire, 2004) remain almost the same in the last 50 years, there is a wide variability of methods and applications to develop their main components a PSHA, and compute hazard estimates. In addition, national seismic hazard maps must usually be updated following design guidelines standards or to provide the most reliable science available to decision makers and scientific community in general. Then, for a specific country more than a model (or several versions of it) can exist (or co-exist), making the selection an issue.

Based on the state-of-the-art of PSHA at regional and national level described by Gerstenberger et al. (2020) and the principles and concepts that should be considered during the creation of a PSHA model proposed in Pagani et al. (2015), a set of parameters was defined to drive the selection process. The parameters were divided in five modules. In Table 1 the parameters considered for each module are summarized.

Table 1: Main characteristics of modern NSHM model.

1. Basic Datasets
Earthquake catalogue
Active fault database
Strong-motion database
Site characterization database
PSHA modelling
2. Documentation describing model preparation
Scientific participation and review process
Codes and tools used to build the model
NSHM model
Seismic Source Model
3. Area sources
a. Grid sources
Crustal Faults
Subduction Faults
Non-parametric ruptures
Ground Motion Model
Tectonic regionalization
b. Models for shallow seismicity (active, stable)
Models for subduction seismicity (interface, intraslab)
Models for deep seismicity (not subduction)
Models for volcanic seismicity

Site response Model
GMPEs based
Site-response analysis
c. Uncertainty Model
Epistemic uncertainty method
Included in Seismic Source Model
Included in Ground Motion Model
Included in Site-Response Model
4. Input hazard description
Documentation describing input files
Input files
5. Calculation and Results
Software used
Hazard curves
Hazard maps
Uniform Hazard Spectra
Disaggregation
Stochastic event sets
Ground motion fields

The first module is related with the basic data needed to build a PSHA national model (NSHM from herein) and its availability. The second one, following the GEM principles of transparency and reproducibility, refers to the methodology and codes used to create the NHSM and the documentation describing the process. The third module is dedicated to NSHM components: the typology of sources included, if a tectonic regionalization was used, which are the ground motion models included and which were the epistemic uncertainties considered. The availability of the input model files, and the associated documentation is crucial and is included into the module 4. The last module is related with the calculation process (i.e. software used and its availability) and the results released with the NHSM model. In the next sections, we review the models available for each country following the criteria described in Table 1.

2.3 Colombia

2.3.1 Seismotectonic Settings

The Colombian territories are located into a complex tectonic setting in the Northern Andes (see Figure 3). The interaction of several lithospheric plates (Nazca, South America, Caribbean, North Andes) and blocks (Chocó-Panama, Coiba, Malpeló) produces different degrees of deformation and seismic activity.

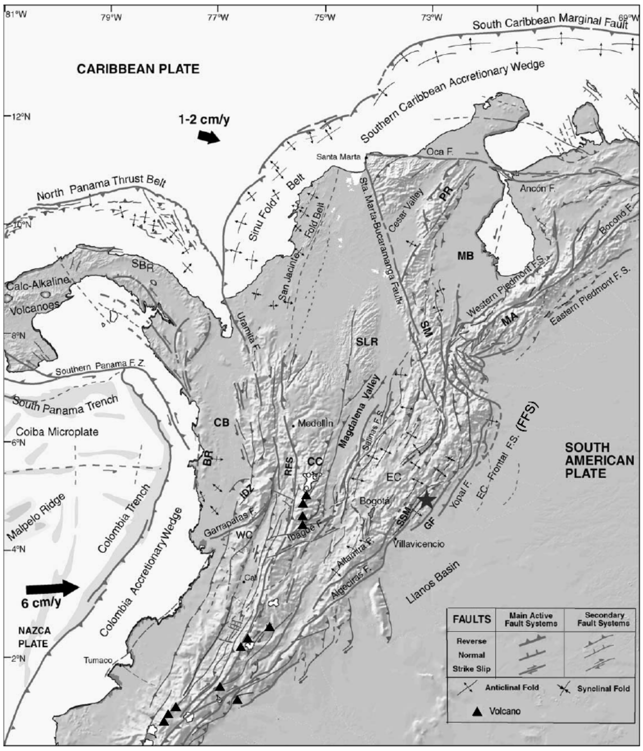


Figure 3. Neotectonic map of Colombia with the main fault systems. Solid black triangles indicate volcano locations. Black arrows indicate plate velocity relative to South America. CB, Panama-Chocó Block; WC, Western Cordillera; CC, Central Cordillera; EC, Eastern Cordillera; RFS, Romeral Fault System Source: Pulido (2003).

The Nazca oceanic plate underneath at 6 cm/year the continental plate (South America) producing high seismicity and several large subduction events in the Ecuador-Colombia segment (e.g. 1906 M8.8 and 2016 M7.8 earthquakes). The Nazca subduction provokes important degree of deformation and faulting in the continental plate as well, creating three mountain Andes ranges (western: WC, Central: CC and Eastern (EC) Cordillera), and several crustal fault systems. The most important are the Romeral Fault System (Central Cordillera), and the Frontal Fault System (Eastern Cordillera). The Romeral Fault System (RFS) is one of the most active and continuous fault systems in Colombia (700 km total length), representing the transition between obducted oceanic crust (west of the fault system) and continental crust to the east. Some segments of RFS are active, generating low and medium seismicity and rarely significant event, such as the 1983 Popayan M5.5 and the 1999 Armenia M6.2 earthquakes. The Frontal Fault System (FFS) extends for almost 1000 km from Ecuador to Venezuela, bounding the Eastern Cordillera. In the southern part, NE right-lateral strike slip style predominates, while in the central part, reverse and trust motion segments are more frequent. Major historical and instrumental events had been associated to this fault system (e.g. 1827 Timana M7.7; 1834 Sibundoy M7.0 and 1967 Neiva M7.2 events).

The eastward movement of the Caribbean plate relative to the South America plate affects the northern region of Colombia, creating the Southern Caribbean Accretionary Wedge (see Figure 3). The convergence rate is low (1-2 cm/yr) and the seismicity associated to this process is not significant.

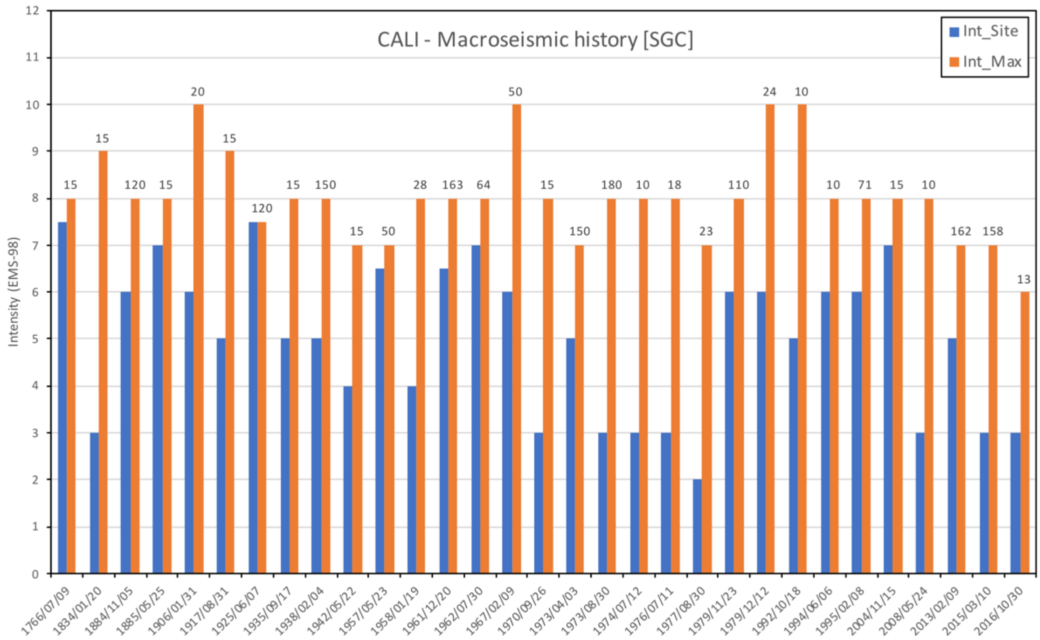


Figure 4. Macroseismic history of Cali city in the last 250 years. In blue the intensity value (EMS-98 scale) felt in the city, in orange the maximum intensity reported by SGC. The labels at the top of the columns are the depth of the events. Source: this report using SGC data.

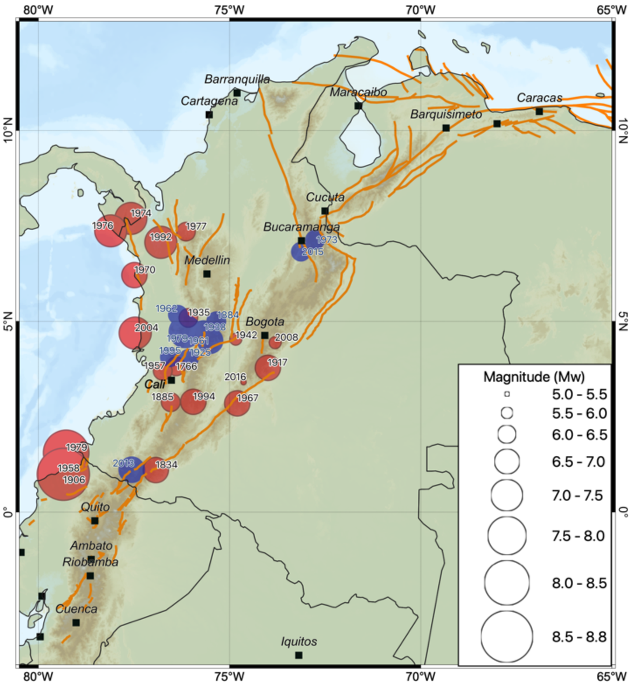


Figure 5. Earthquakes felt in Cali city in the last 250 years. In red interface and crustal events (depth <= 50 km), in blue in-slab and deep events. Labels are the year reported in the SGC catalogue. Orange lines represent the major crustal active faults in the region. Source: this report using SGC and GEM data.

According to the macroseismic history compiled by the SGC (see Figure 4 and 5), Cali city have been affected several times in the past for subduction and crustal events. Intensities larger or equal to VII (MSK scale) had been reported in 1766, 1885, 1925, 1962 and 2004. The maximum intensities reported (VII-VIII, MSK scale) are associated to: the 1766 M6.5 Buga-Valle del Cauca event, with an estimated depth of 15 km. The 1925 M6.1 Tulua-Valle del Cauca earthquake, Mendoza et al. (2004) suggested that it was a subduction event with a depth larger (120 km) than those proposed by Engdahl and Villaseñor (2002) – 35 km -, which seems not to be coherent with the macroseismic intensities reported and the local tectonic.

2.3.2 Previous studies

In the last 50 years, several institutions and organizations have been involved in the construction of NSHM models in Colombia. The first generation of NSHM was proposed by Estrada-Uribe and Ramirez (1977) in terms of macroseismic intensity (MMI scale). After the 1983 Popoyan destructive earthquake, a seismotectonic probabilistic study was carried out by Garcia et al. (1984). For this study, a new parametric catalogue was compiled and 22 seismic sources characterizing the subduction and the crustal seismicity were defined. The hazard map, in terms of PGA for a 10% of probability exceedance in 50 yr (see Figure 6), showed a quite different spatial distribution.

Figure 6. –. PGA with 10% probability of exceedance in 50 years proposed by Garcia et al., (1984). Source: Modelo Nacional de Amenaza Sísmica para Colombia (SGC-GEM, 2018).

The highest values are located, mainly, along the pacific coast, demonstrating the direct influence of Nazca subduction zone. The contribution of crustal sources is here more evident too (0.25 – 0.30 along the region covered by the FFS). This map was used as a reference for the Colombian building code (CCCSR-84).

In 1996 a scientific collaboration between several national organizations made possible a new estimation. In this multidisciplinary framework, basic information and datasets were updated and improved using local data. Key advances in the modelling include the consideration of 32 active faults, epistemic uncertainties related with geometry, maximum magnitude and seismicity associated to the fault sources (see more details in AIS-UNIANDES-INGEOMINAS, 1996).

The hazard map obtained in terms of PGA for a 10% of probability exceedance in 50 yr (see Figure 7) represents the average values between 25 different alternatives. The hazard values are similar to those obtained by Garcia et al. (1984). This map was the reference seismic zonation for a new version of Colombian building code (NSR-98).

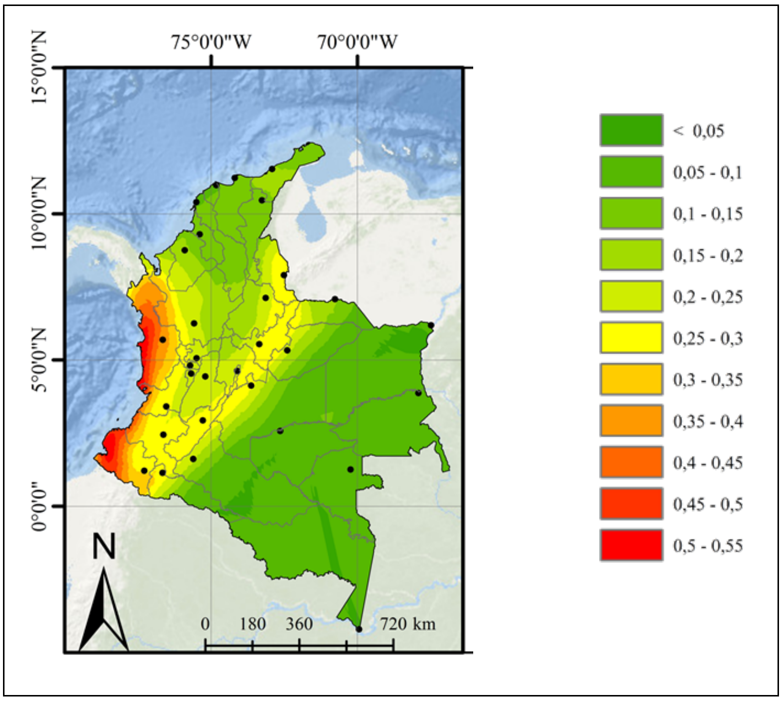


Figure 7. –. PGA with 10% probability of exceedance in 50 years proposed by AIS-Uniandes-Ingeominas (1996). Source: Modelo Nacional de Amenaza Sísmica para Colombia (SGC-GEM, 2018).

During the last decade, the Colombia Geological Survey (SGC) carried out a long-term program to perform seismic hazard model at a national scale in collaboration with local and foreign organizations. The first NHSM model was created in 2010 in the framework of a scientific collaboration with the National University of Colombia (Ingeominas-Universidad Nacional, 2010). Key advances in the modelling include a) creation of a homogenised catalogue, b) the classification of seismicity according with the tectonic environment present in the region, c) the Bucaramanga nest was considered as a seismic source of intermediate and deep seismicity.

Figure 8 presents the hazard map proposed for a 10% of probability exceedance in 50 yr in terms of PGA (in cm/s). Here, the contribution of shallow seismicity is more pronounced in the north-western region close to Panama. The hazard values obtained along the pacific coast are one order different than those obtained by previous studies.

In the same period, AIS (2009) performed a PSHA study with the aim of obtaining a new reference zonation in order to update the Colombian building code. The SSM contains 38 area sources, 30 accounting for active shallow seismicity and the rest associated to subduction and deep (not subduction) tectonic environments. Events in the depth interval comprised between 0 and 60 km were considered as shallow seismicity, events with larger depth were assigned to intermediate and deep seismic sources. The fault sources were defined as area sources, which were assigned all the events around a buffer of 30 km. Interface and intraslab sources were defined to the Nazca subduction zone.

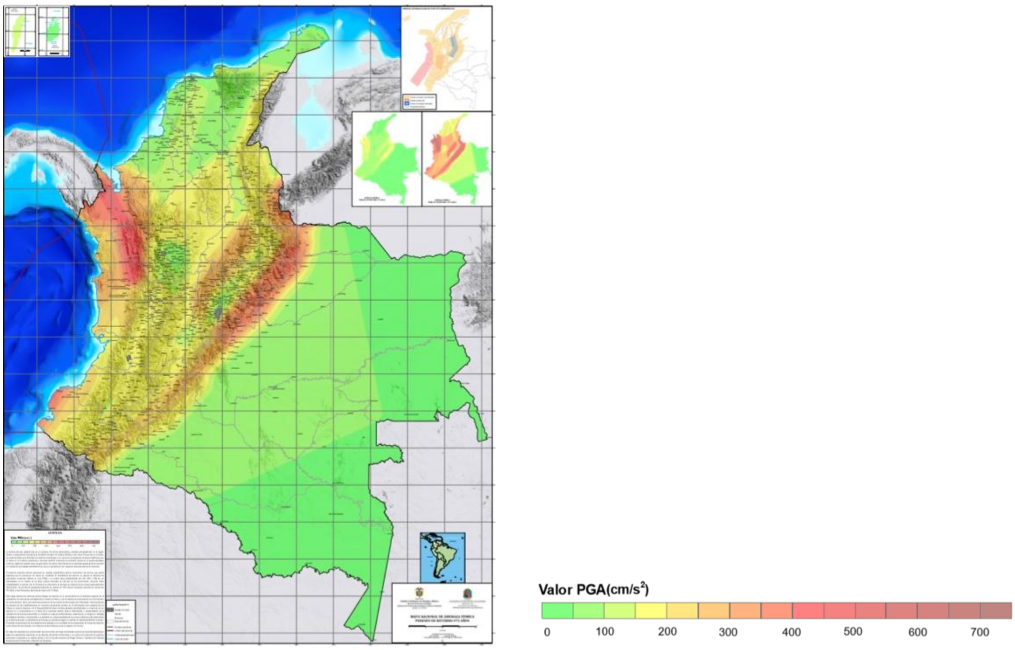


Figure 8. –. PGA with 10% probability of exceedance in 50 years proposed by Ingeominas-Universidad Nacional (2010). Source: Modelo Nacional de Amenaza Sísmica para Colombia (SGC-GEM, 2018).

In the SSM, epistemic uncertainties related to the b-value of the magnitude-frequency distribution and the maximum magnitude were considered. In the definition of the GMM, a comparison between the ground-motions observed and those predicted by GMPEs (pre-selected) was performed. For the computation of hazard, the software CRISIS (v.2007, Ordaz et al., 2003) was used. Hazard curves and maps for several return periods (i.e. 31, 225, 475, 1000 and 2500 years) and imts (PGA and spectral acceleration at 0.1, 0.3, 0.5, 1.0 and 2.0 seconds) were obtained. Uniform hazard spectra (UHS) were derived using these spectral periods. As an example, the hazard map for PGA with a return period of 475 years, which corresponds to a 10% probability of exceedance in 50 years. The highest values are located in the boundaries between Panama and Colombia and Venezuela (400 – 600 cm/s^2).

By the other hand, a scientific collaboration between the SGC and the GEM Foundation has recently produced new results (and NSHM model) for Colombia. This collaboration benefits of a new homogeneous earthquake catalogue compiled by the SGC, using historical and instrumental data. A multidisciplinary approach improved the knowledge about active tectonic and crustal deformation in the country (Arcila et al., 2017) and this led to the development of a complex SMM. This SMM has four components accounting for the seismicity generated within the different seismotectonic environments identified:

- An active shallow source model, containing 30 independent area sources, defined using polygons delineating regions with homogeneous temporal and spatial characteristics of seismicity, tectonic and geodynamic setting.
- The second component, related to the same tectonic environment, was built integrating active faults and distributed seismicity sources. Overall, it consists of 9 wide distributed seismicity sources (modelled as a grid of point sources) and 171 fault sources. The magnitude frequency distribution for point sources close to faults were truncated at Mw6.5 to prevent double counting of seismicity.
- The subduction component considers seismic sources associated with interface and intra-slab seismicity. The interface sources were modelled as large "complex" faults (see description about this source typology in Pagani et al. 2014) and two alternative models (i.e. segmented and un-segmented) were considered. A set of non-parametric ruptures were used to model the intra-slab seismicity. Details about rupture geometries and rates can be found in SGC-GEM (2018) and in Pagani et al. (2020). Two alternative model were considered too for this component.
- The last component characterizes the deep seismicity not related to the Nazca subduction zone. In this case, the seismicity was divided into two segment and a set of non-parametric ruptures were defined for each segment.

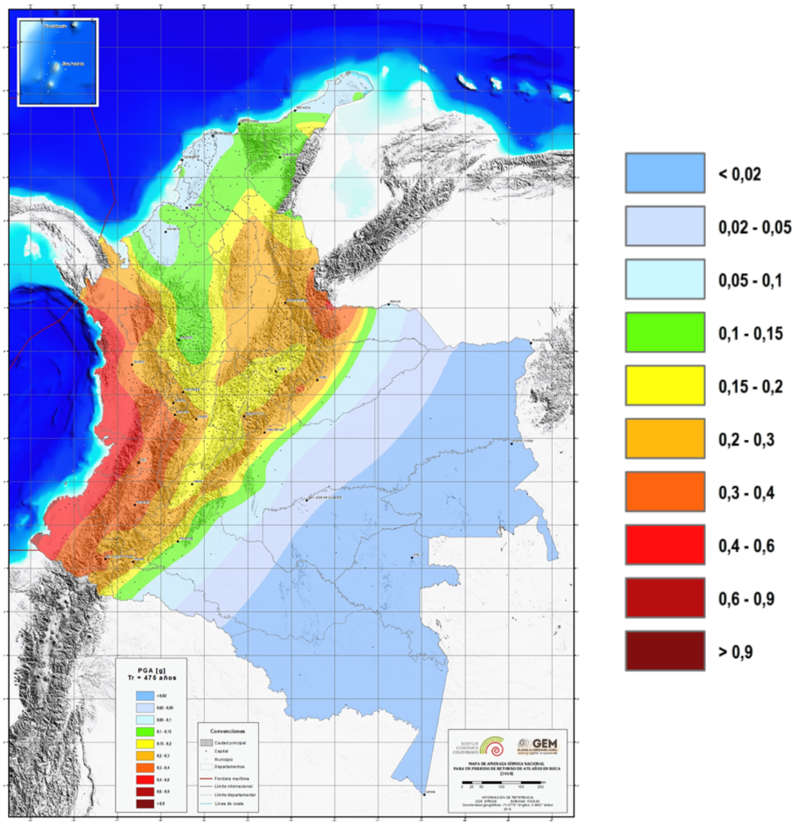


Figure 9. –. PGA with 10% probability of exceedance in 50 years proposed by SGC-GEM (2018). Source: Modelo Nacional de Amenaza Sísmica para Colombia (SGC-GEM, 2018)

The GMM benefits of the strong-motion recordings collected by the SGC, which made possible to perform an accurate selection of the most appropriate GMPEs for the different tectonic environment considered. The selection process involved three main steps: a) pre-selection of candidate GMPEs following Cotton et al. (2006) and Bommer et al. (2010), b) comparison (using trellis plots) of predicted ground motion using rupture scenarios consistent with ruptures modelled by the SSM and c) data-to-predicted ground motion comparison using observed ground-motion from SGC recordings and ground motion predicted by the pre-selected GMPEs.

In the current version of the SGC-GEM model, epistemic uncertainties related with both, SMM and GMM, were considered.

For the computation of hazard, the OpenQuake software (Pagani et al., 2014) was used. Hazard curves and maps for several return periods (i.e. 31, 225, 475, 975 and 2475 years) and imts (PGA and spectral acceleration at 0.1, 0.2, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 seconds) were obtained. Uniform hazard spectra (UHS) were derived using these spectral periods. Disaggregation analysis were performed for a group of selected cities. As an example, the hazard map for PGA with a return period of 475 years, which corresponds to a 10% probability of exceedance in 50 years, is presented in Figure 9. As expected, the highest hazard values are distributed along the pacific coast, where the hazard is dominated by the contribution of subduction interface sources and some shallow active faults in the boundary between Colombia and Panama (Choco region). A second spot arise near the Colombia-Venezuela border, where the contribution of crustal faults largely contributes to the hazard obtained. In the rest of the country, smaller hazard values are observed.

2.4 Ecuador

2.4.1 Seismotectonic Settings

Ecuador, as Colombia, is located in north-western South America. The Nazca subduction, which is underneath the continental plate with a NE direction and relative plate motion of ~60 cm/year (Nocquet et al., 2009), is the first cause of intense seismic activity. The location and geometry of the subducting slab is conditioned by two major topographic structures (Carnigie ridge and Grijalba rift, see Figure 10), which complicate the penetration of the Nazca plate beneath the continent. Recent studies suggest that these structures play a crucial role in the interplate coupling and the continental deformation (Yepes et al. 2016, Chlieh et al., 2014; Trenkamp et al., 2002).

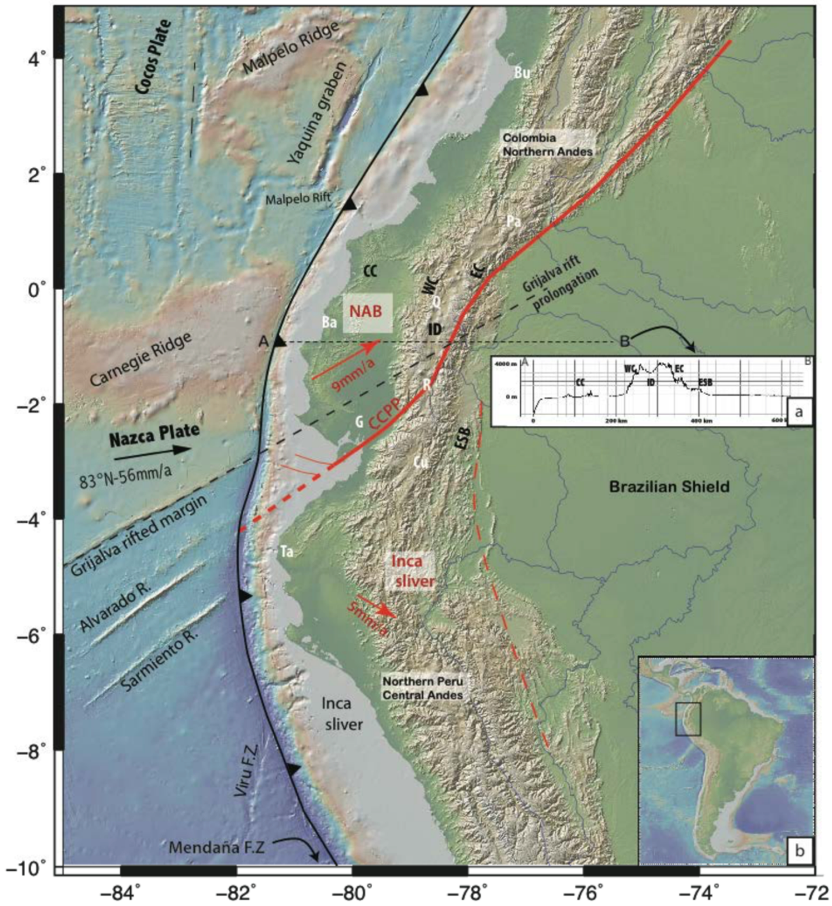


Figure10. Geodynamic framework of Ecuador. Source: Yepes et al. (2016).

The interaction with other active plates (North Andean Block and South America) provokes an important deformation from SW (Guayaquil Gulf) to NE, generating crustal faulting and moderate to large shallow seismicity across Ecuador. These events are, mainly, associated to transpressional fault systems located along the boundary between the North Andean Block and the South America plate. Deformations within these plates generate also moderate seismicity. The largest event associated to the Pacific subduction was recorded in 1906 (M8.8) along the coast, near Colombia, but moderate and large crustal seismicity in the Andes Mountain Ranges are recorded too (e.g. 1949 M6.8 and 1987 M7.1 events).

Then, the seismicity in Ecuador is quite high and events with magnitude larger than 5.0 are frequent. In the past century, Ecuador has experienced more than 15 events with magnitude ≥ 7.0.

Three seismotectonic regimes can be recognised: a) subduction interface; b) subduction in-slab sources, which are associated to Nazca subduction zone; and, c) shallow active sources within the continental plate and along the boundary between the NAB and SA

More than 20 earthquakes have been felt in Quito with macroseismic intensity larger than V in the las 500 years. Historical records recognized damages (intensity VII and larger) produced by events in 1587, 1755, 1797, 1859 and 1868 (Del Pino and Yepes, 1990). The 1755 earthquake, associated to Quito fault, is considered the most destructive event affecting Quito (Del Pino and Yepes, 1990). The maximum intensity associated was IX (MSK scale) and extensible and generalized damages were reported anywhere with collapse of churches and the Cathedral. Damaging earthquakes affecting Quito occurred not only in the immediate vicinity of the city. Events that occurred at 150 km (e.g. destructive Riobamba 1797 M8.3 earthquake) produced significant damages in Quito (Egred, 2004).

In the last century, several large subduction events have been felt in the city (e.g. 1906, 1938, 1942, 1998, 2006), producing moderated damages and medium intensities ranging from IV to VII in Quito. The most important last damaging event occurred in 1987. The 5 March, M6.9 main earthquake and its aftershock (more than 18000 events) produced significant damages in the city (maximum intensity = IX, MSK scale). In addition, this event generated important secondary perils like landslides and floods.

2.4.2 Previous studies

As reported in recent studies (Beauval et al. 2018; Parra et al. 2016), the first probabilistic hazard study dedicated to update the Ecuadorian Building Code was performed in 2001 (CEC, 2001). The SSM contained 53 area sources, for two tectonic environments (subduction interface and crustal). The resulting hazard zonation referred to 10% of exceedance probability in 50 years sub-divided the country in 4 seismic zones. Unfortunately, there is no technical documentation about this model.

The building code was updated in 2015, in the framework of a French-Ecuadorian scientific collaboration. The seismic zonation was based on a single best-estimate model (i.e. epistemic uncertainties were not included) from an earlier version of the NSHM model proposed later on by Beauval et al. in 2018.

In 2016, Parra et al. (2016) obtained seismic hazard estimation at a national scale. The methodology adopted follows classical (Cornell,1968; McGuire, 2004) seismotectonic probabilistic approach. The SSM contains 13 area sources associated to the active shallow crustal environment, 3 sources characterizing the subduction interface seismicity and 4 sources describing the occurrence of events in the in-slab tectonic environment. The faults are not considered as sources, but they were used to compute the maximum magnitude and as a good estimator of the aleatory uncertainty related to this parameter. The GMM was defined following Arango et al. (2012) recommendations. Then, several GMPEs were used for each tectonic environment, considering the epistemic uncertainty related with the Ground Motion characterization.

The seismic hazard calculation was performed using the software CRISIS2012 (v5.5, Ordaz et al. 2013). Hazard curves and maps for a reference rock soil, for several return periods (475, 975 and 2475 years) and imts (PGA and spectral accelerations at 0.1, 0.2, 0.5, 1.0 and 2.0 seconds), were obtained. Uniform hazard spectra and hazard disaggregation results were computed for four important cities.

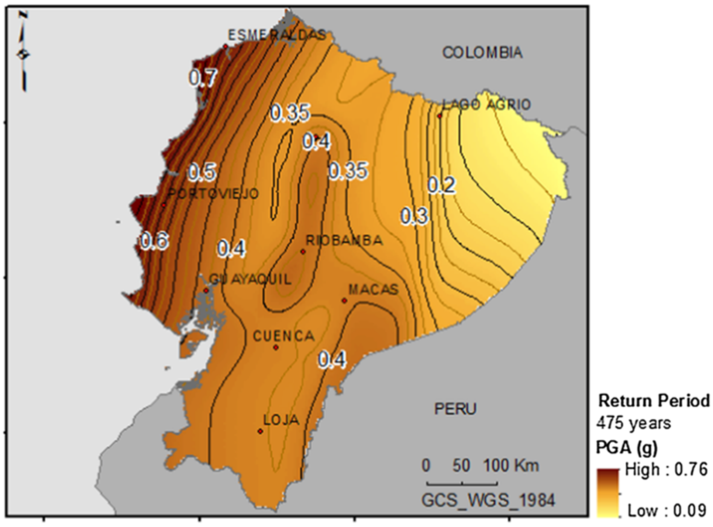


Figure 11. – Mean PGA with 10% probability of exceedance in 50 years proposed by Parra et al. (2016). Source: Parra et al. (2016)

The hazard map for PGA with a return period of 475 years, which corresponds to a 10% probability of exceedance in 50 years, is presented in Figure 11. The highest hazard values (0.70 g) are located along the Ecuadorian coastline. The hazard decreases eastwards, with high values in central highlands and reaching lower values (0.2 – 0.1 g) in south-eastern Ecuador. The fault contribution is not evident in the hazard map, but the disaggregation results obtained (e.g Quito) show the clear controlling of crustal events associated to shallow active faulting (Quito fault system).

Finally, as was mentioned before, Beauval et al. (2018) proposed the last (new) estimation of NSHM for Ecuador. This model benefits on a long-time scientific collaboration, relying on the most up-to-date information available in the country. Historical earthquakes were studied by Beauval et al. (2010), providing new locations and magnitudes. The instrumental seismicity information was reviewed, and a new homogenized catalogue was created combining historical and instrumental earthquakes (Beauval et al., 2013). The active tectonic knowledge was significatively improved (Alvarado et al. 2014, 2016), as well as the understanding of the complex geodynamic related to plate tectonic interactions (Chlieh et al., 2014; Nocquet et al., 2014, 2016). These improvements favoured the definition of a new seismic source model (SSM) by Yepes et al. (2016). The SSM contains a set of 19 seismic sources to model earthquake occurrences associated to a) active shallow crustal sources (fault and area sources), b) subduction interface sources, and, c) in-slab subduction sources.

The SMM contains area sources enclosing the main active fault system along the boundary between the NAB block and the SA plate. Two large background area sources were included to account for diffuse seismicity not associated with the faults considered. The catalogue was the main resource used to characterise the area sources, while for the faults the earthquake recurrence was inferred from geodetic and/or geologic slip rates.

The segmentation of the subduction interface sources proposed by Yepes et al. (2016) was revised after the 2016 Pedernales M7.8 event. The Esmeraldas segment was extended 50 km farther to the south. Older Bahia segment was then reduced and now called “La Plata”. As a possible consequence of this modification, this segment could not host large mega-interface quakes. The Talara segment was subdivided into two new segments. The authors considered this new segmentation more consistent with the interseismic coupling information derived from GPS data and recorded history of large subduction earthquakes in Ecuador. Currently, the SSM contains four interface sources.

The intraslab seismicity was modelled into volumes defined at increasing depths to model the variations of the slab along dip direction. The Grijalva rift separates two different subducting plate domains. The most active Farallon domain contains four dipping volumes, while the Nazca domain contains two dipping volumes. In Yepes et al. (2016) a detailed description about the definition of the intraslab sources can be found.

For the characterization of the sources, three alternative earthquake catalogues were used. In addition to the Ecuador homogeneous catalogue, an ISC-based catalogue and a NEIC-based catalogue were considered. The uncertainties related to the process of building a homogeneous catalogue motived this choice. Then, three alternative recurrence models were included in the logic tree. The GMM was defined using published models. Three GMPEs for interface and intraslab sources and three for shallow active sources were selected, considering the epistemic uncertainty related with the Ground Motion characterization into the analysis. In the SSM logic tree, epistemic uncertainties related to two alternative models (area model and fault model) were considered. The use of three diverse recurrence rates leads to 12 alternative source models. The final logic tree (including the GMM logic tree) contains 324 different combinations. The calculations were performed using the OpenQuake engine software (Pagani et al. 2014). The results published are referred to mean PGA and for a return period of 475 yrs, for a reference soil with Vs30 = 760 m/s (see Figure 12). The highest PGA values are located along the coast in the north-western region (larger than 0.5 g). Higher values (larger than 0.4 g) are present inside the Cordillera. The lowest values are located in the north-eastern region.

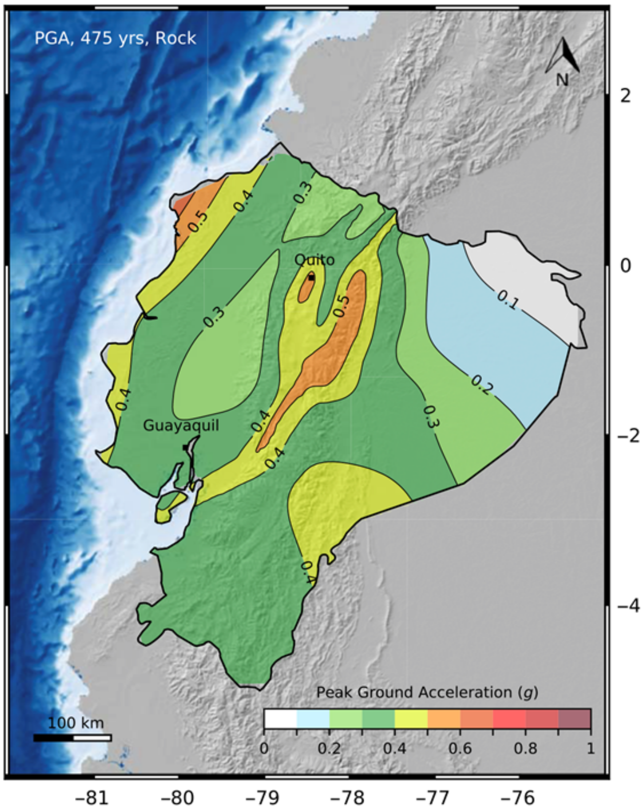


Figure 12. –. Mean PGA with 10% probability of exceedance in 50 years proposed by Beauval et al. (2018). Source: Beauval et al. (2018)

2.5 The Dominican Republic

2.5.1 Seismotectonic Settings

The Dominican Republic is part of The Hispaniola, an Island of the Greater Antilles arc at the north-eastern boundary between the North America and the Caribbean Plates. As recognized by several authors (Mann et al., 1995; Benford et al., 2012), it is a wide zone accommodating the east-northeastward motion (18 – 20 mm/yr) of the Caribbean Plate relative to the North America Plate (DeMets et al., 2000). This direction caused a maximum oblique convergence (and subduction) of the oceanic Atlantic lithosphere under Puerto Rico and the Hispaniola.

Recent studies (Mann et al. 2002; Benford et al., 2012; Calais et al., 2016), based on GPS measurement, propose a tectonic model composed by four microplates and several tectonic blocks (i.e. Hispaniola, Gonave, Caribbean, and North Hispaniola, see Figure 13), which is more consistent with both, GPS and geologic data, than a simple strike-slip bending model (Mann et al., 1984) or a north-south convergence between the two plates involved.

In the Hispaniola, the plate motion is partitioned between shortening and strike-slip faulting. The shortening produced by the subduction is accommodated by several folds and thrusts in the central part of the Island, producing mountain ranges and valleys (e.g Massif de la Selle in Haiti and Cordillera Central in Dominican Republic). Two major, left-lateral strike-slip fault systems: the Septentrional Fault

(SF) to the north and the Enriquillo-Plaintain Garden Fault (EPGF) to the south, limit this block, known as the Hispaniola microplate.

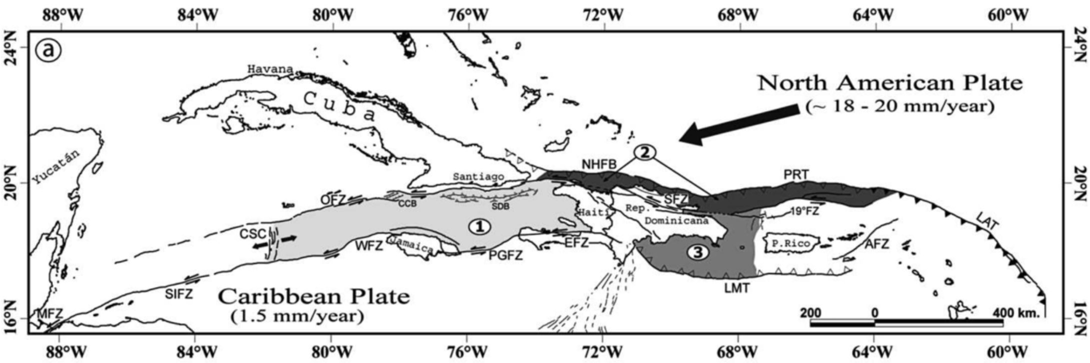


Figure 13. –. Main tectonic features of the northern Caribbean-North America plate boundary zone. The numbers indicate the tectonic model proposed by Mann et al. (2002): 1) Gonave microplate, 2) Septentrional microplate, and, 3) Hispaniola microplate. Source: Garcia et al. (2008)

In the long-term seismic activity recorded for the Hispaniola region (see Figure 14) there are large events occurred along the limits of this complex plate boundary. In the 16th century the most important earthquake is located in Santiago de los Caballeros. During the 18th century several large events occurred along the southern coast of the island, in the Enriquillo Plantain Garden Fault System (1751b, 1770) and Los Muertos deformed belt. The north coast of the Hispaniola had been affected several times by large and destructive earthquakes. In Haiti two significant events occurred in 1842 and 1887, while the northern part of the Dominican Republic suffered a series of six large events (between 1943 and 1953) along the subduction zone from central Hispaniola (1946 M7.8 event) to the northwest corner of Puerto Rico (Dolan and Wald, 1998). Five of these earthquakes had mainly reverse mechanisms and were associated with the subduction interface.

The 1946 M8.1 (reverse faulting and tsunamigenic) earthquake and the sequence of associated events (1946 – 1953; see Dolan and Wald, 1998) demonstrated the seismogenic potential of the subduction interface offshore Hispaniola. Other large historical ruptures (e.g. 1897 M6.8 event) had been associated to subduction by Kelleher et al. (1973) and ten Brink et al. (2011).

Finally, the 2010 Haiti destructive event, associated to a secondary structure (Léogâne fault) of the Enriquillo - Plantain Garden Fault System (Calais et al., 2010) confirms that all these major faults, due its seismogenic potential, must be explicitly considered in any hazard calculation.

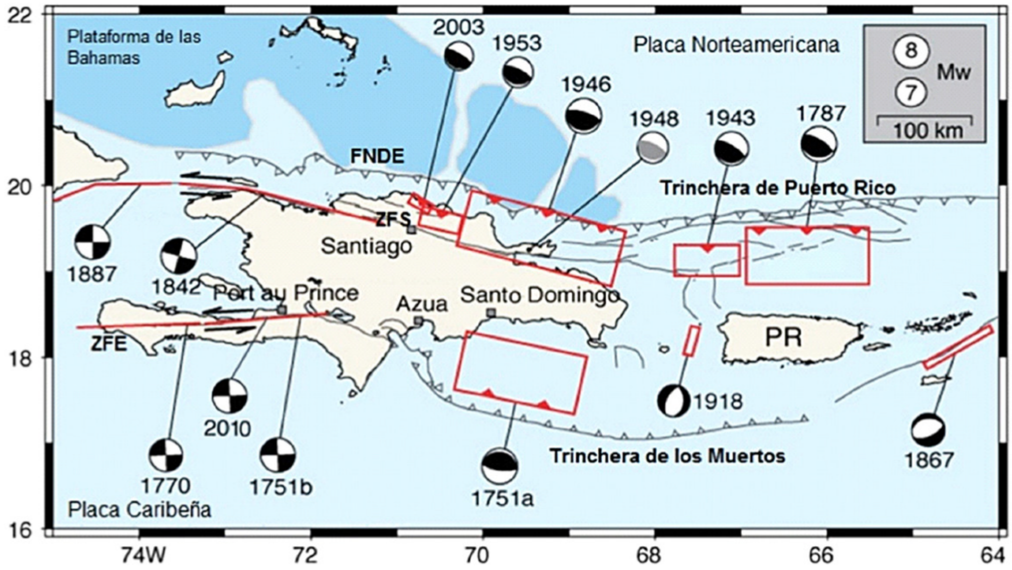


Figure 14. –. Main tectonic features and focal mechanisms of larger events for the Hispaniola region. Source: Llorente et al. (2017)

As was mentioned before, Santiago de los Caballeros city was completely destroyed by the 1562 event (del Monte and Tejada, 1890). At that time, the city was located on the Septentrional fault trace (Mann et al, 1998) and must be abandoned and rebuilt 10 km to the SE. Using Bakun and Wentworth (1997) methodology, ten Brik et al (2011) located the event 15 km south of the Septentrional fault and estimated a magnitude of M7.7.

The 1842 earthquake generated extensive damage along northern Hispaniola. The most important damages were reported in Haiti (e.g. Cap Haitien, Port-de Paix), but significant damages (IX-VIII, MMI scale) were also reported in Santiago de los Caballeros by Scherer (1912). The location estimated was 10 km west of Santiago de los Caballeros and the estimated magnitude was M7.6. Subduction events like the 1946 M7.9 caused moderate damages (VIII-VII, MMI scale) in Santiago de los Caballeros. Also, Prentice et al. (2003) performed several tectonic trenches along the Septentrional fault and suggested that the last large event on the fault (near Santiago de los Caballeros) occurred 800-1000 years ago.

2.5.2 Previous studies

A reference NHSM for the Dominican Republic, as far as we know, is not available. After the 2010 M7.0 destructive Haiti event, Frankel et al. (2011) performed a preliminary PSHA for the Hispaniola (see Figure 15). However, the authors indicate that, for the Dominican Republic, were not considered all the possible seismic sources affecting the eastern part of the Hispaniola and for this reason, results and model proposed cannot be considered as complete.

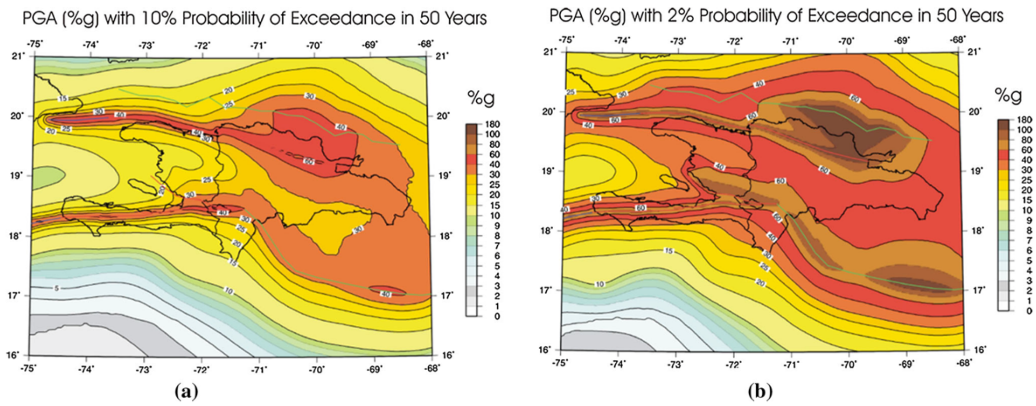


Figure 15. –. Mean PGA (in %g) with a) 10% of probability of exceedance in 50 years and b) 2% probability of exceedance in 50 years for the Hispaniola, proposed by Frankel et al. (2011). Source: Frankel et al. (2011)

However, the seismic zonation (and hazard maps, see Figure 16) included in the Dominican Republic building code (R-001, 2011; "Reglamento para el Análisis y Diseño Sísmico de Estructuras") will be used as a valid reference. Unfortunately, there is no technical documentation about the PSHA study (model) used in R-001 (2011).

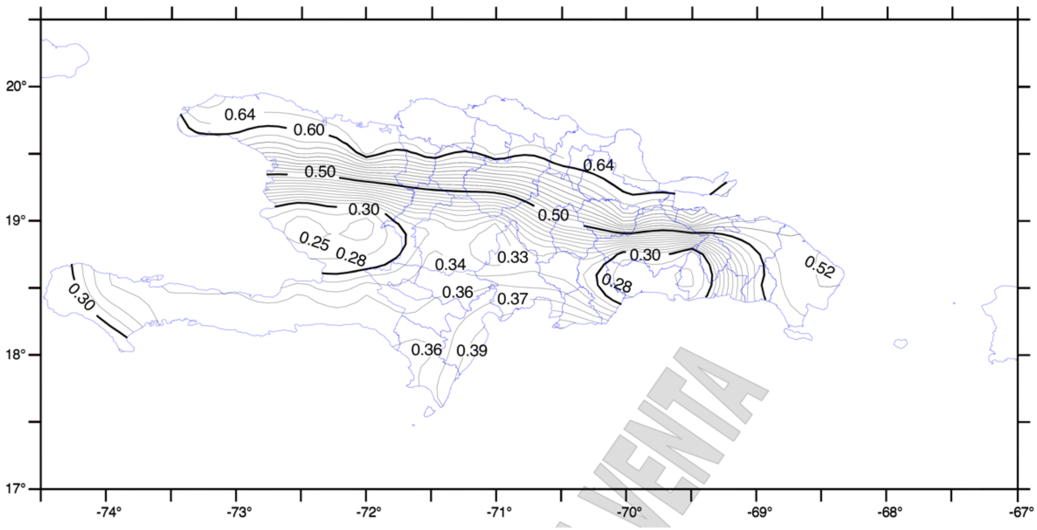


Figure 16. –. PGA with 2% probability of exceedance in 50 years proposed by R-001 (2018). Source: R-001 (2011)

Then, we plan to fill this gap, building a new NHSM model for the Dominican Republic in the framework of the TREQ project. To support this, we will use all the information compiled for the region and the seismic model developed in the framework of the CCARA project (CCARA project, https://ccara.openquake.org/), a GEM regional collaboration project funded by USAID and improved "a posteriori" by the GEM hazard team during the last two years.

This model (and the information related) covering the Central America and the Caribbean region (CCA) was built as a combination of a shallow component, where distributed seismicity sources and active faults had been integrated; and a subduction component, conformed by several subduction models (i.e. Central America, Lesser Antilles, Puerto Rico – North Hispaniola), all of them divided into its main components (interface and in-slab).

The SSM includes 3D "single" fault sources combined with point sources modelling active shallow seismicity. Also, 3D “complex” fault sources are used to account for subduction interface shallow seismicity. The seismicity associated with the intermediate and deep subduction seismicity had been modelled using 3D ruptures, which are constrained within the volume of the slab. The GMC includes a set of GMM for each of the tectonic environment considered. The GMMs was obtained using residual analysis approach, which compares strong ground-motion data with values predicted by a set of candidates GMPEs.

The calculation was done using OQ engine (Pagani et al, 2014) for peak ground acceleration (PGA) and spectral acceleration (SA) at 0.2s, 0.5s, 1.0s, and 2s on a grid of approximately 10 km-spacing with reference soil conditions corresponding to a shear wave velocity in the upper 30 meters (Vs30) of 760-800 m/s. A set of hazard and risk results is available at https://maps.openquake.org/.

We have to point out that the CCA model was created without any local information from Haiti or the Dominican Republic. This “gap” of knowledge will be filled with the inclusion of data/information from local institutions collaborating with TREQ project activities like SGN (Dominican Republic Geological Survey), the UASD University and SODOSISMICA. In particular, seismicity information from local compilations and new or improved data about crustal active faults will be used to build the new hazard national model.

2.6 Selected NSHM models

Given the information compiled about the most recent (and available) NSHM in Colombia, Ecuador and the Dominican Republic, and the criteria defined in section 2.2, the following models were selected:

- For Colombia, the SGC-GEM (2018). The main characteristics of this model are presented in Table 2. This model is suitable to compute hazard results on rock conditions for Cali, but a further improvement will be necessary due to the Cauca-Cali-Patia fault is not considered as an active source. On the contrary, the INGEOMINAS-DAGMA (2005) authors considered this fault potentially active and its contribution to the total computed hazard is significative.

Table 2: Main characteristics of SGC-GEM (2018) NSHM model.

1. Basic Datasets	
Earthquake catalogue	Available
Active fault database	Available
Strong-motion database	Available
Site characterization database	Not available
2. PSHA modelling	

Site response Model	
GMPEs based	YES
Site-response analysis	Not included
c. Uncertainty Model	
Epistemic uncertainty method	Logic Tree
Included in Seismic Source Model	YES

Documentation describing model preparation	Available
Scientific participation and review process	
Codes and tools used to build the model	Available
3. NSHM model	
a. Seismic Source Model	
Area sources	Included
Grid sources	Included
Crustal Faults	Included
Subduction Faults	Included
Non-parametric ruptures	Included
b. Ground Motion Model	
Tectonic regionalization	Included
Models for shallow seismicity (active, stable)	Included
Models for subduction seismicity (interface, intraslab)	Included
Models for deep seismicity (not subduction)	Included
Models for volcanic seismicity	Not included
Included in Ground Motion Model	YES
Included in Site-Response Model	NO
4. Input hazard description	
Documentation describing input files	NO
Input files	YES
5. Calculation and Results	
Software used	OpenQuake
Hazard curves	Grid of locations and sites
Hazard maps	Grid of locations and sites
Uniform Hazard Spectra	Grid of locations and sites
Disaggregation	Selected sites
Stochastic event sets	Not considered
Ground motion fields	Not considered

- For Quito, we considered the Beauval et al. (2018) model as the best option. The authors provided to TREQ a simplified version of this model, but the results obtained for Quito using this simplified version are similar to those published in Beauval et al. (2018). Then we considered this version of the model suitable to be used for the Quito calculation on TREQ. The main characteristics of the model are presented in Table 3.

Table 3: Main characteristics of Beauval et al. (2018) NSHM simplified model.

6. Basic Datasets	

Earthquake catalogue	Not available
Active fault database	Not available
Strong-motion database	Not available
Site characterization database	Not available
7. PSHA modelling	
Documentation describing model preparation	Available
Scientific participation and review process	
Codes and tools used to build the model	Available
8. NSHM model	
a. Seismic Source Model	
Area sources	Included
Grid sources	Included
Crustal Faults	Included
Subduction Faults	Included
Non-parametric ruptures	Not included
b. Ground Motion Model	
Tectonic regionalization	Not available
Models for shallow seismicity (active, stable)	Included
Models for subduction seismicity (interface, intraslab)	Included
Models for deep seismicity (not subduction)	Not considered
Site response Model	
GMPEs based	YES
Site-response analysis	Not included
c. Uncertainty Model	
Epistemic uncertainty method	Logic Tree
Included in Seismic Source Model	YES
Included in Ground Motion Model	YES
Included in Site-Response Model	NO
9. Input hazard description	
Documentation describing input files	NO
Input files	YES
10. Calculation and Results	
Software used	OpenQuake
Hazard curves	Grid of locations
Hazard maps	Grid of locations
Uniform Hazard Spectra	Selected sites
Disaggregation	Selected sites
Stochastic event sets	Not considered
Ground motion fields	Not considered

Models for volcanic seismicity	Not considered

- For the Dominican Republic, a new NSHM model will be built in the framework of TREQ. The Central America and the Caribbean (CCA-GEM, 2019) regional model will be used as backbone. The development of the model largely depends on the information (and scientific collaboration) provided by local organizations. We planned to receive a huge contribution from the SGN (National Geological Survey) which must lead and coordinate the hazard activities in this country, in particular regarding the tectonic active knowledge and fault data parametrization. Other contributions are coming from the UASD University, which shared information related with local seismicity. The main characteristics of the CCA-GEM (2019) model are presented in Table 4.

Table 4: Main characteristics of GEM-CCA (2018) regional model.

11. Basic Datasets	
Earthquake catalogue	Available
Active fault database	Available
Strong-motion database	Not available
Site characterization database	Not available
12. PSHA modelling	
Documentation describing model preparation	Available
Scientific participation and review process	
Codes and tools used to build the model	Available
13. NSHM model	
a. Seismic Source Model	
Area sources	Not included
Grid sources	Included
Crustal Faults	Included

Site response Model	
GMPEs based	YES
Site-response analysis	Not included
c. Uncertainty Model	
Epistemic uncertainty method	Logic Tree
Included in Seismic Source Model	NO
Included in Ground Motion Model	YES
Included in Site-Response Model	NO
14. Input hazard description	
Documentation describing input files	NO
Input files	YES
15. Calculation and Results	
Software used	OpenQuake
Hazard curves	Grid of locations
Hazard maps	Grid of locations

	Subduction Faults	Included
	Non-parametric ruptures	Included
b.	**Ground Motion Model**	
	Tectonic regionalization	Included
	Models for shallow seismicity (active, stable)	Included
	Models for subduction seismicity (interface, intraslab)	Included
	Models for deep seismicity (not subduction)	Not considered
	Models for volcanic seismicity	Not considered

Uniform Hazard Spectra	Selected sites
Disaggregation	Selected sites
Stochastic event sets	Not considered
Ground motion fields	Not considered

3 COMPILATION OF LOCAL DATASETS

As was mentioned before, the assessment of seismic hazard at an urban scale largely relies on local and detailed information. The overall goal will be to compute seismic hazard in each city using a set of amplification functions in combination with bedrock results obtained using the reference hazard model selected. However, the selection of the methodologies to be used in TREQ largely depends on the quantity and quality of the available information and data. The contribution of local organizations collaborating with GEM was crucial in this process. For Cali, the Colombian Geological Survey, the OSSO Corporation and the spatial data infrastructure office of Cali are the major contributors. The municipality of Quito provided information and data related with the microzonation study performed by ERN in 2012, as well as other basic information. For Santiago de los Caballeros, the Geological Survey contributed with information and data associated with geological, geomorphological and tectonic at a national level and detailed information regarding the Santiago de los Caballeros microzonation study.

To facility the compilation, a list of the local information (and data) needed was provided to each city (see Spanish version in Table 5).

Table 5: Ideal input data list required to perform PSHA at local scale including in the analysis site-response and secondary perils.

HAZARD INPUT DATA
Previous information
- [REQUIRED] Reference to any previous site-response and microzonation study, including datasets and results collected if possible
Geographic/geomorphic information
- [REQUIRED] High resolution digital elevation model. This is also needed for secondary perils e.g. landslides
Geological information
- [REQUIRED] Geological map (with the highest resolution possible and ideally in digital format)
- [optional] Geomorphological map (with the highest resolution possible and ideally in digital format)
- [optional] 3-dimensional geological models (e.g. models that describe shape and materials filling a sedimentary basin)
- [REQUIRED] Borehole stratigraphies (ideally in digital format)
Geotechnical information
- [REQUIRED] If shear-wave velocity profiles are not available, CPT and SPT profiles
- [optional] Shear modulus and damping Vs. strain curves
Geophysical information
- [REQUIRED] Shear-wave velocity profiles (from downholes, MASW, SASW)
- [optional] Results of seismic refraction surveys
- [optional] Results of microtremor measurements
Seismological information
- [optional] Weak-motion recordings collected by dense-seismic networks (typically for local site-response analysis)
- [REQUIRED] Strong-motion recordings (these will be used to perform 1D ground response analysis) + information on strong-motion stations

In the following sections we describe the available information and data provided by the local institutions collaborating with TREQ for each considered city. Most of the compiled information regards seismic microzonation studies and the geological, geophysical and geotechnical investigations performed in the framework of these studies. At the end of the section dedicated to each city, the available information is summarized, following the ideal case presented in Table 5.

3.1 Cali city, Colombia

The Santiago de Cali (or Cali) city, is the capital of the Valle del Cauca department in southwest Colombia. The city (see Figure 14) is located in a flat area between the Western and Central Cordilleras, in the western margin of the Cauca Valley. According with the last census (DANE 2018, Cali en Cifras 2018-2019), Cali is the most populous and fastest-growing economy city in southwest Colombia.

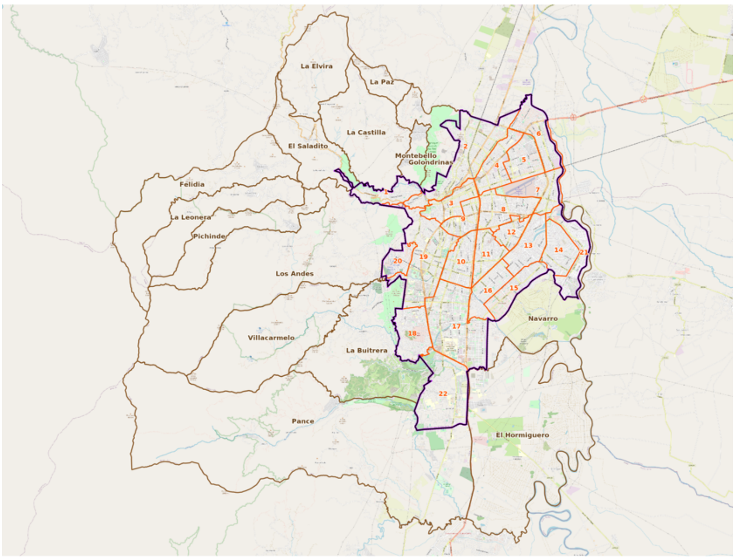


Figure 14 The Cali urban area. Source: idesc.cali.gov.co/geovisor.php

The city, located at 70 km east the Nazca subduction, is mainly affected by subduction seismicity (i.e. interface and intermediate-depth intraplate seismicity from the Benioff zone), but historical records demonstrate the capability of shallow seismicity from near and far important crustal faults.

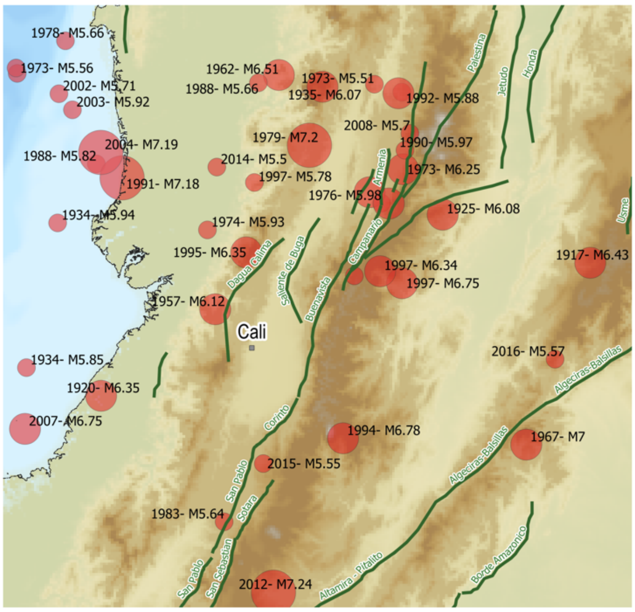
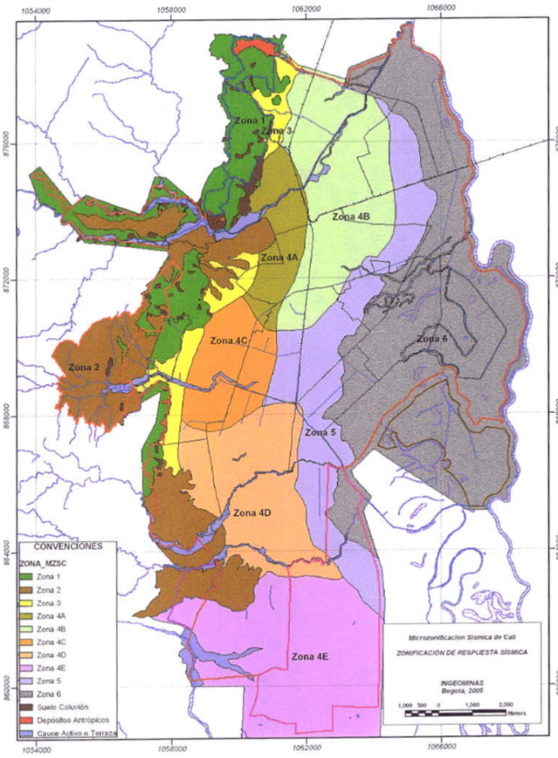


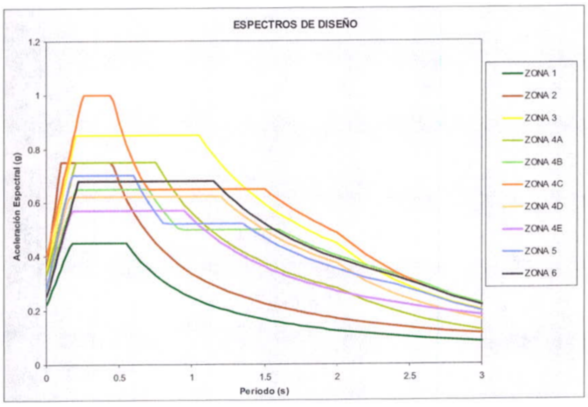
Figure 315 Seismicity and faults in the Cali city region. Events with magnitude larger than 6.0 from the ISC-GEM (v.7.0) catalogue. Active crustal faults from the SGC active fault database

From 1566 more than 20 events occasioned important damages in the city. The major events (see Figure 15) are the 1979 Manizales (M7.2) and Tumaco (M8.1), and the 1983 Popayan (M5.7) earthquakes. Also, Cali is the most exposed city with the highest seismic hazard classification according with the last Colombian building code (NSR-10, 2010).

3.1.1 Previous studies

The occurrence of large and destructive events affecting the region (i.e. Tumaco and Popayan earthquakes) promoting detailed investigations in Cali. The most important and extensive are those performed by OSSO (Meyer et al., 1990) in 1990 and INGEOMINAS-DAGMA (INGEOMINAS, 2005) in 2005. In the INGEOMINAS-DAGMA microzonation study different geophysical, geological, and seismological approaches were performed to improve the seismotectonic knowledge at a regional scale and the construction of a detailed geotechnical model for the city. The project was subdivided in several sub-projects (i.e. geology, geophysics, seismotectonic, seismic hazard, geotechnics, site-response) and the results, available at the Cali Municipality website (https://www.cali.gov.co/dagma/publicaciones/49685/estudios_ambientales_dagma/) were compiled in several reports, describing the work done at both, regional (i.e. seismic hazard evaluation) and local (i.e. geotechnical measurements and detailed geological and geophysical mapping) scale. In the microzonation zoning obtained (Figure 16) the city was divided in into 10 zones with similar dynamic soil behavior. A response spectrum was computed using detailed site-response analysis (equivalent-linear and non-linear) and 10 events for each zone.





a) b)

Figure 16 a) Microzonation zoning and b) response spectra for Cali. Source: Ingeominas-Dagma (2005)

3.1.2 Geological and geomorphological information

The Western and Central Cordilleras (see Figure 17) are located parallel to the Pacific coast and limiting the Cauca Valley basin, which according to Nivia (2001) and INGEOMINAS-DAGMA (2005) has a basement of volcanic igneous rocks on which lie tertiary sedimentary rocks and quaternary deposits. In the central part of the Valley, where the Cali city is located, heterogeneous and thick alluvial quaternary deposits are present. These geological units are large alluvial cones ("fans") associated to torrential flows of the rivers (i.e. Cañaveralejo and Cauca rivers). The geomorphology of the Cauca Valley corresponds to a unit of fluvial origin, characterized by alluvial "fans" deposits with a smoot slope, which are interdigitated and limited by the Cauca River plain.

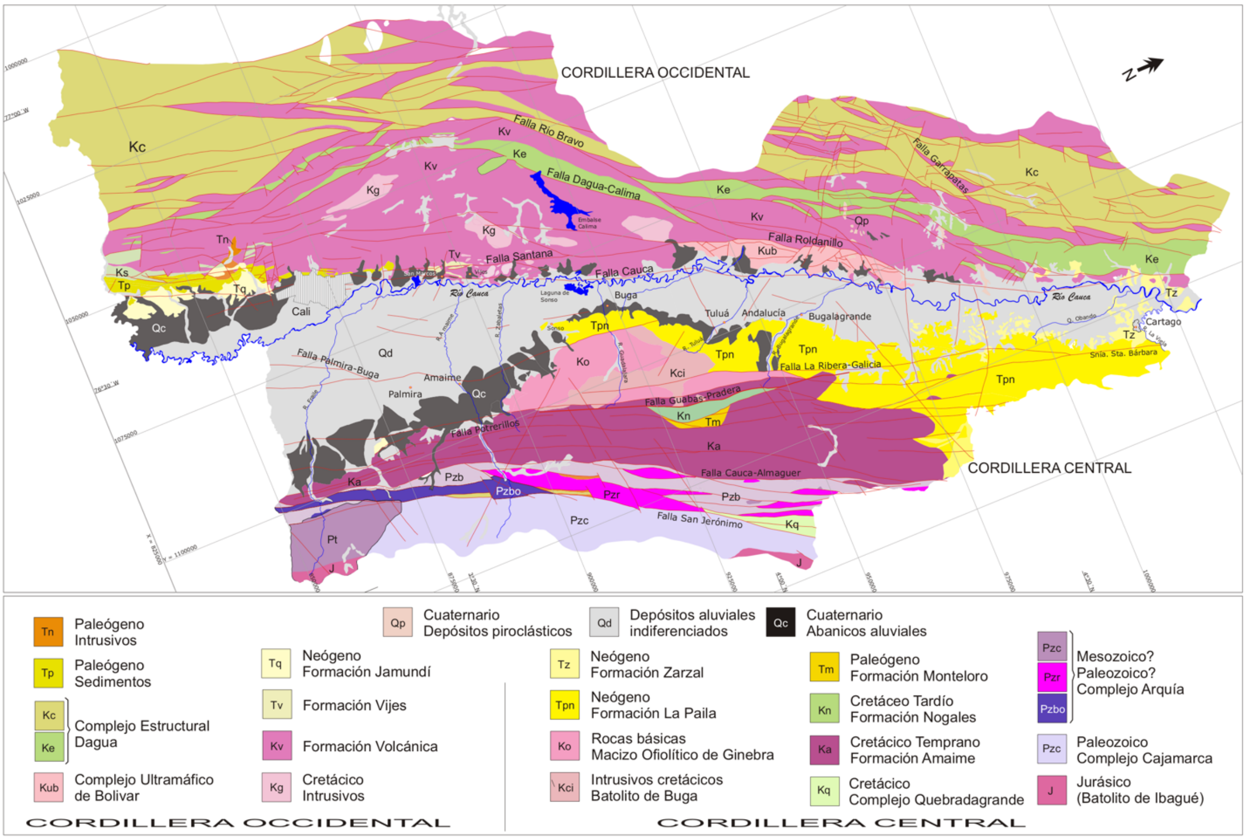


Figure 17 Geological map of the Cauca Valley region. Source: Lopez (2006)

The Western Cordillera is mainly composed by oceanic rocks, which were accreted during the Mesozoic and early Cenozoic. During the late Cenozoic, thrust and fold belts are associated with the subduction process, and the volcanic rock units constitute most of the Western Cordillera rocks, including the hills around Cali. These units are composed by basaltic lavas, diabase, and gabbro intrusions. In general, these rocks are affected by faulting and then, a large degree of fracturing is also observed. In the Cali region, these units extend from the Menga area (northern limit of the city) to the Cañaveralejo river basin in the southern part.

The Central Cordillera is composed by pre-Mesozoic basement (see Figure 17), which includes oceanic and continental rocks. The basement rocks are intruded by late? Mesozoic and Cenozoic plutons related to the subduction. Recent magmatic activity from current active volcanoes is concentrated along the crest of the Cordillera. The Central Cordillera is limited by important reverse faults systems, which root beneath the mountain range. The Romeral fault system limited the western flank and has been active since the Oligocene, with strike-slip and reverse ruptures (movement).

For the city, INGEOMINAS-DAGMA (2005) produced detailed geological and geomorphological maps (1:20 000). These maps are available in PDF format and was shared by the CGS to TREQ. In addition, lithostratigraphic description of some boreholes are available too (ANEXO GT2 DESCRIPCION LITOLOGICA.pdf).

3.1.3 Geophysical information

During the microzonation study performed by INGEOMINAS-DAGMA, several geophysical studies were performed at both, regional and local scale. At a regional scale, gravity, electromagnetic and seismic techniques were used to:

a) create geophysical models, maps, and cross sections,

b) improve the knowledge of underlying structures, spatial distribution of anomalies,

c) map the subsurface below the Cauca Valley.

For instance, in the residual gravity anomaly map obtained (Figure 18) several important tectonic structures can be recognised, as: the Cauca-Patia fault, in the western boundary of Cali city, the Palmira-Buga fault, in the central part of the Valley and the Guabas-Pradera fault in the Western Cordillera.

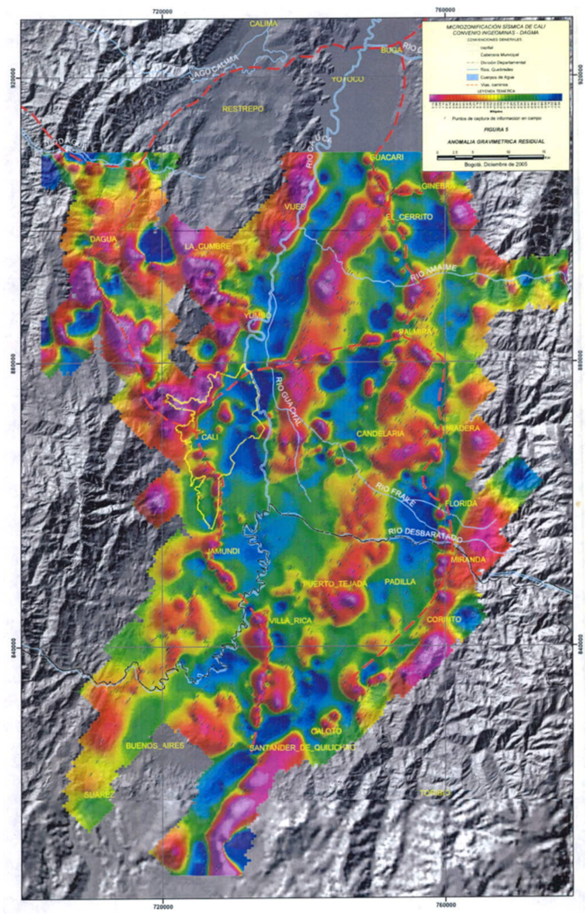


Figure 18 Residual gravity anomaly map for the Cauca Valley. Source: Ingeominas-Dagma (2005)

Two reference regional gravity cross sections were obtained using gravity modelling. In the first one, located at north of Cali (see Figure 19), the structural features mentioned before can be identified, as well as three major units: quaternary deposits poor consolidated with an average density of 1.7 g/cm^3; tertiary units with an average density of 2.4 g/cm^3; and the bedrock (volcanic rocks) with an average density of 2.8 g/cm^3.

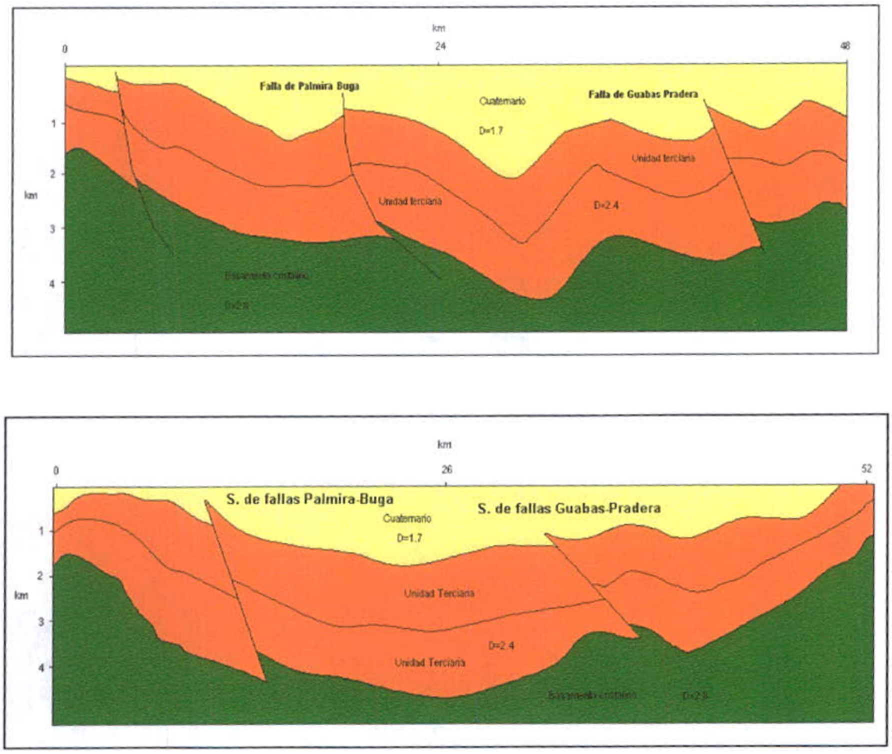


Figure 19 Regional gravity cross section for the Cauca Valley: a) at north of Cali and b) at south of the City. Source: Ingeominas-Dagma (2005)

As expected, the maximum quaternary thickness is located in the central part of the valley at a depth of 2 km. The bedrock depth varies in a depth range of 2.0 near the western margin of the Cauca Valley, to 4 km in the central part and 2.5 km in the Western Cordillera. In the second cross section, which is situated at south of Cali, the deformation of the Cauca basin is smaller, but the units are affected by the faults as in the previous case. The depth of the quaternary deposits is lower, and the bedrock depth is larger.

The seismic reflexion lines located in the east to west direction, provide a similar interpretation. As shown in the seismic line VC-04-79 of Figure 20, the features (i.e. faults) and structural units obtained by the gravity modelling are easily recognizable. However, some new irregularities due to secondary faults or changing of the paleo-topography of the basement, not described by the gravity modelling, can be identified.

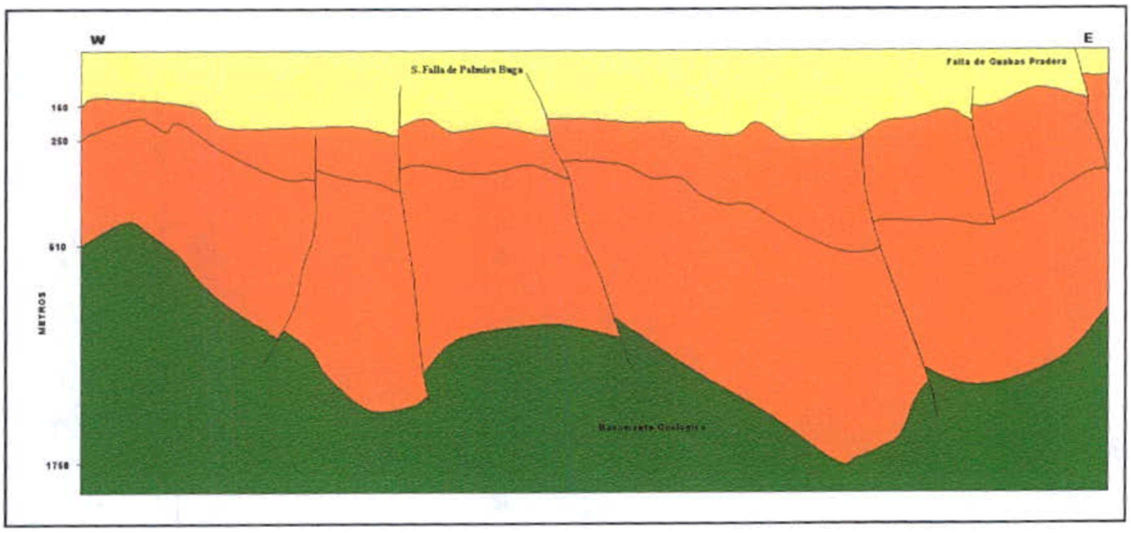


Figure 20 Interpretation of seismic reflexion line VC-79-04. Source: Ingeominas-Dagma (2005)

The geophysical local investigations performed in Cali provided additional and more detailed information. An extensive gravity campaign was performed and two maps describing the contacts between the three units founded for the urban area of the city were created. The first map, describing the depth between the quaternary and the tertiary units, is not included in the information shared by the Cali municipality. The second one, describing the contact between the tertiary rock and the bedrock, is presented in Figure 21 In general, the depth of the quaternary sediments increases towards the east, being deeper in the Navarro sector (2.6 km), and in the northern part of the city (Floralia area) with a depth of 2.3 km. On the west side, the average thickness decreased, and two anomalous regions can be identified: the Cañaveralejo sector and northern part of the city where the bedrock depth reach a depth of 1.8 km.

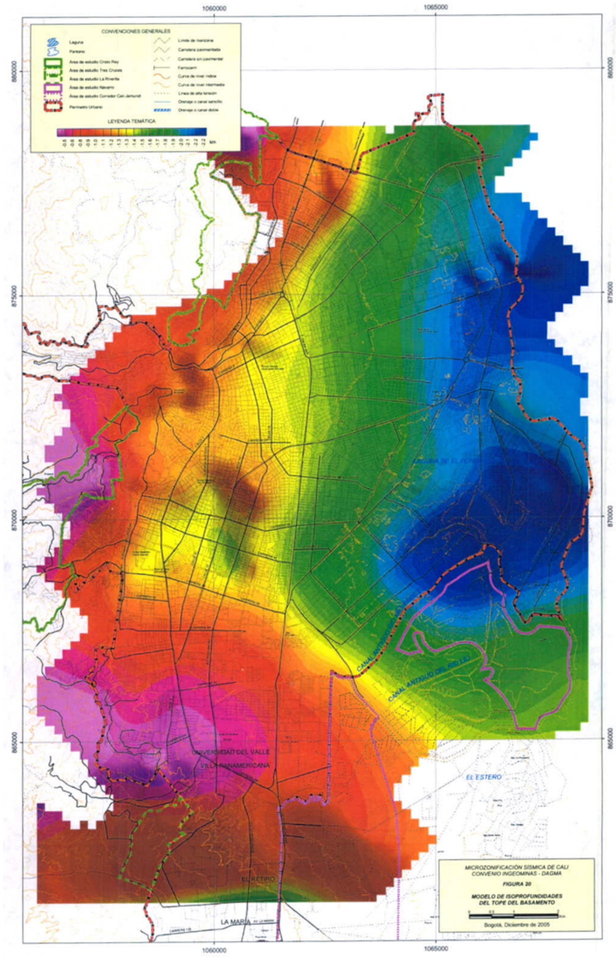


Figure 21 Depth of the bedrock obtained from gravity modelling. Source: Ingeominas-Dagma (2005)

Seismic refraction lines were performed and used to identify the propagation velocity of the longitudinal (Vp) and transversal (Vs) waves in the city. The geologic units were used in the interpretation of the seismic refraction lines, providing for each cross section the variation of the Vp and Vs velocities on depth considering the different geologic units. The geologic units were sub-divided into sub-classes when for the same geologic unit significant variations of the velocity on depth were identified. This variability was associated to several factors like depth of the groundwater level, compaction, and fracturing.

The main result from this investigation was an acceptable correlation between the geological units, the materials present in these units and the Vp and Vs velocities. A summary of this correlation is shown in Table 6, additional information can be found in the tables provided in the Annexes 10 and 11 of the INGEOMINAS-DAGMA (2005) related report

(https://www.cali.gov.co/publico2/documentos/dagma/estudios_ambientales/CONTRATO022002/TOMO1CONVENIO022002.pdf)

The geophysical investigation provided acceptable models describing the sub-surface below the Cauca Valley and the city, describing the geometry (i.e. depth bedrock, thickness of geologic units) of the geologic units, its lithographic characteristics and variations of Vp and Vs velocities. These results constituted an important input for the site effect modelling at an urban scale.

Table 6 Summary of the Vp and Vs velocities obtained from seismic refraction modelling and its correlation with the geologic and lithologic units in the Cali city area. Source: Ingeominas-Dagma (2005)

V_P, m/s	V_s, m/s	Unidad	Correlación Litológica
450-825	450-660	Qab1	Suelos limo-arcillosos, cantos, clastos en matriz limo-arenosa seca.
900-1100	740-850	Qab2	Suelo limo-arcilloso,arcillas, limos arenosos parcialmente saturados.
1150-1375	950-1114	Qab3	Suelo orgánico, gravas y arenas parcialmente saturadas a saturadas.
1575-1900	1292-1720	Qal1	Materiales de gravas, arenas de diferente tamaño de granos saturados con agua y en menor proporción lentes arcillosos y limo arcillosos.
2150-2660	1940-2250	Qal2	Arcillas semi-compactas, limos arcillosos, limos arenosos con ocasionales niveles arenosos saturados.
785-1020	650-810	Qlc	Suelos limo-arcillosos, limos arenosos y arenas de parcialmente saturadas a saturadas.
470-650	420-575	TQj1	Suelos rojizos limosos secos con ocasionales vestigios de clastos alterados, matriz arenosa seca.
2000-2100	1650-1920	TQj2	Depósitos de gravas y cantos no consolidados mal seleccionados de basaltos, cherts, conglomerados, areniscas y otras rocas con matriz limo-arenosa parcialmente saturada.
2300-2600	1985-2175	TQj3	Depósitos de gravas y cantos no consolidados mal seleccionados de basaltos, cherts, conglomerados, areniscas y otras rocas con matriz limo-arcillosa.
1900	1585	Tog1	Predominio de intercalaciones de areniscas secas, alteradas y fracturadas sobre arcillolitas.
2700-2740	2250-3170	Tog2	Intercalaciones de arcillolitas y areniscas saturadas, alteradas y fracturadas.
3240-3900	2625	Tog3	Intercalaciones de arcillolitas y areniscas sanas.
710-800	640-675	Qfv	Depósitos fluvio torrenciales clasto soportados con aporte volcánico compuestos por bloques, cantos y gravas en matriz limo-arcillosa húmeda.
800	700	Kva1	Suelo residual y diabasas alteradas secas.
1800	1400-1500	Kva2	Diabasas alteradas y fracturadas con permeabilidad secundaria.
3800	2350	Kvf	Diabasas fracturadas secas.
3900-3950	2800-3500	Kv1	Diabasas sanas con poco fracturamiento.
4400-4450	4100-4120	Kv2	Diabasas Sanas.

3.1.4 Geotechnical information

The geotechnical investigations performed during the INGEOMINAS-DAGMA (2005) microzonation study constitute the major contributor for the current knowledge of the dynamic characteristics of soils in the city.

The goal of the geotechnical investigations was to subdivide the city in quasi-homogeneous regions with similar geotechnical characteristics: materials, mechanical properties, etc.

The first step was to compile a Database of Geotechnical Data (DGD) using the information available from public and/or private soil studies in the city. More than 1000 studies, almost 5000 sites and 28000 samples were compiled. The average depth was 8 meters, with 10 sites by km^2. A preliminary classification of the materials and their spatial and on-depth distribution was obtained using this information.

To explore and describe the characteristics of the soils at depth larger than those described in the DGD, geophysical (i.e. detailed seismic refraction and reflection, microtremors, gravity) and geotechnical (i.e. boreholes, downholes, CPTU, DMT, CPT) studies, as well as laboratory analysis (i.e. cyclic triaxial), were carried out at an urban scale. All this information was summarised and spatially distributed into 30 cross-sections covering the city.

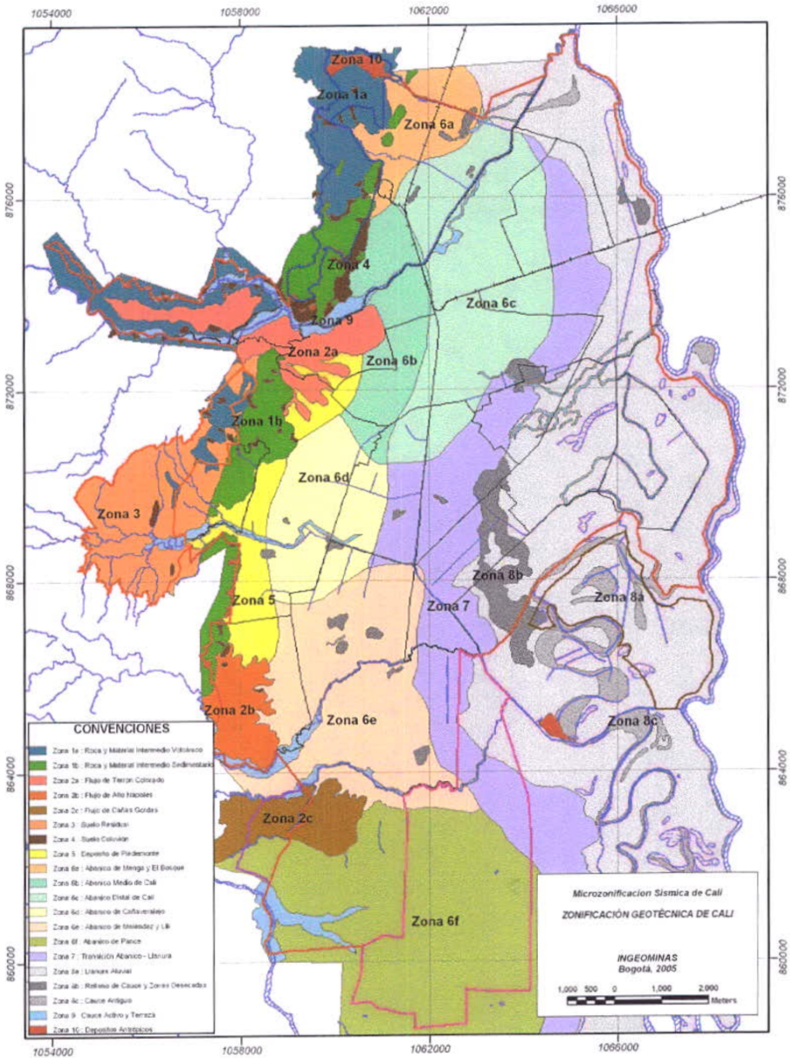


Figure 22 Microseismic zonation for Cali. Source: Ingeominas-Dagma (2005)

The city was subdivided in ten zones with similar characteristics from a geotechnical point of view (see Figure 22 and Table 7). The zonation was obtained integrating the local geologic and lithological information, detailed geophysical data, spatial distribution of soil in the first 10 meters from the DGD, and the 30 geotechnical cross-sections.

Table 7 Summary of some general characteristics of the geotechnical zones. Source: Ingeominas-Dagma (2005)

ZONA GEOTÉCNICA	NOMBRE	Espesor del Depósito (m)	Periodo Elástico (S)	Unidad Geológica Superficial
1	1a. Roca y material intermedio volcánico		0.1 - 0.2	Rv, Iv
	1b. Roca y material intermedio sedimentario		0.15 - 0.25	Rs, Is
2	2a. Flujo Terrón Colorado		0.25 - 0.5	Sft
	2b. Flujo Alto Nápoles		0.25 - 0.5	Sft
	2c. Flujo Cañas Gordas		0.25 - 0.75	Sfa
3	3. Suelo Residual	5 - 20	0.15 - 0.25	Sv
4	4. Suelo Coluvión	*	*	Sco
5	5. Depósito de Piedemonte	200 - 500	0.75 - 1.25	Sal2
6	6a. Abanico de Menga y Bosque	300 - 500	1.0 – 1.5	Sal2
	6b. Abanico Medio de Cali	50 - 300	0.75 – 1.25	Sal2
	6c. Abanico Distal de Cali	300 - 900	1.25 – 1.75	Sal2
	6d. Abanico de Cañaveralejo	400 - 700	1.5 – 2.0	Sal2
	6e. Abanico de Meléndez y Lili	100 - 400	0.75 – 1.25	Sal2
	6f. Abanico de Pance	100 - 800	0.75 – 1.25	Sal2
7	7. Transición Abanico - Llanura	800 - 1000	1.25 – 1.75	Sal2, Sal1
8	8a. Llanura aluvial	1000 - 1700	1.25 - 2.0	Sal1, Sal4
	8b. Relleno de Cauce y Zonas Desecadas			Sal5
	8c. Cauce antiguo			Sal3, Sal6
9	9. Cauces activos y terrazas	*	*	Sal7
10	10. Depósitos Antrópicos	*	*	Sfe, Sac, Sam
* Según localización y tipo				

3.1.5 Topographic information

In TREQ we will assess the impact of secondary perils on losses, in particular for Cali the hazard produced by landslides triggered by earthquakes will be estimated. Basic but detailed information will be used to compute landslide and liquefaction susceptibility using simplified approaches. Digital elevation models (DEM) are one of the most effective and commonly used tools for estimating slope instability, landslide susceptibility and landslide hazard and risk assessment.

During the microzonation study of Cali performed by INGEOMINAS-DAGMA in 2005, efforts were dedicated to build a DEM (1:10 000 scale) for the region (see Figure 23) using cartographic information provided by the Cali municipality. Unfortunately, this information is no more available and for TREQ we will create a DEM using Shuttle Radar Topography Mission (SRTM, Farr et al, 2007) data.

The Shuttle Radar Topography Mission (SRTM, Farr et al, 2007) is an international research effort to generate the most complete high-resolution digital topographic database of Earth prior to the release of the ASTER GDEM in 2009. The SRTM data are available at the US Geological Survey's EROS Data Center for download.

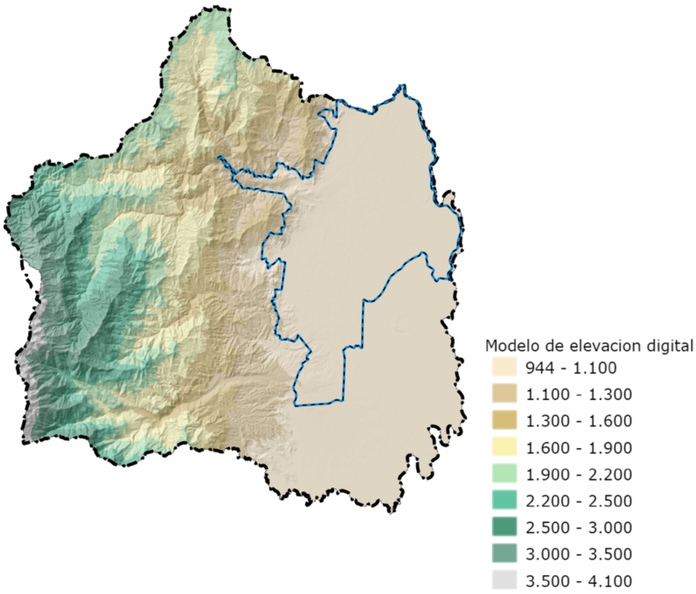


Figure 23 Digital Elevation Model (DEM) for Cali (INGEOMINAS-DAGMA, 2005). Dashed line represents the municipality boundaries and the brown line the city perimeter. Source: Dagma (idesc.cali.gov.co/geovisor.php).

The elevation models are arranged into tiles, each covering one degree of latitude and one degree of longitude. The resolution of the raw data is one arcsecond (30 meters along the equator) and includes elevation data for Africa, Europe, North America, South America, Asia and Australia. The elevation models derived from the SRTM data are intended to be used with a Geographic Information System (GIS) and stored in GIS format (.hgt). In Figure 24 the DEM created for the Cali region using SRMT data is presented.

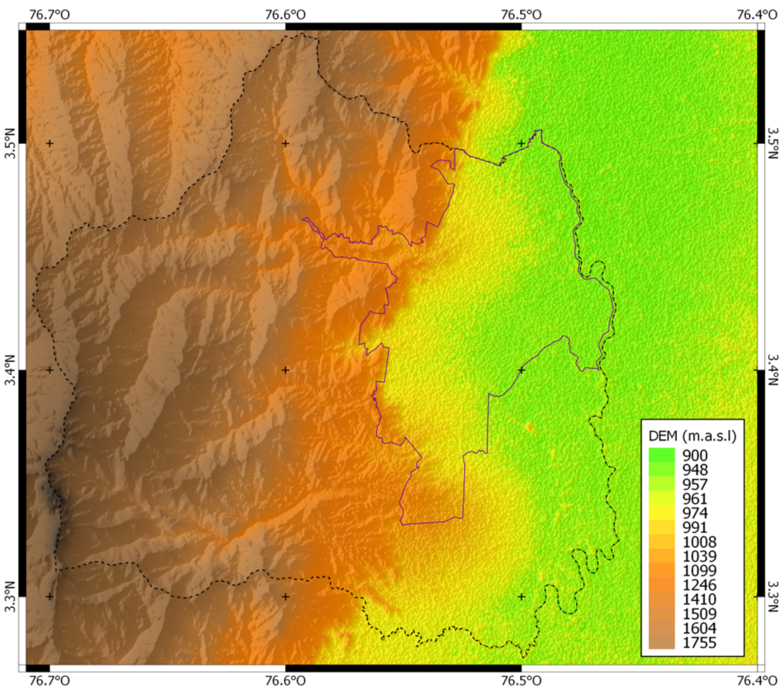


*Figure 24. Digital Elevation Model (DEM) for Cali. Elevation data from the NASA-Shuttle Radar Topography Mission (SRTM). Dashed line represents the municipality boundaries and the brown line the city perimeter. Source: NASA (**https://urs.earthdata.nasa.gov**) and Dagma (idesc.cali.gov.co/geovisor.php)*

3.1.6 Summary

In the table below a summary of the data compiled for Cali and the available formats.

HAZARD INPUT DATA		
	Object	Format
Previous information		
- [REQUIRED] Reference to any previous site-response and microzonation study, including datasets and results collected.	INGEOMINAS-DAGMA. (2005). Estudio de microzonificación sísmica de Santiago de Cali. Bogotá. Ministerio de Minas y Energía Microzonation map of Cali (1:20 000 scale).	Extensive study for Cali. It includes several reports, figures and maps (in PDF format). PDF format (MZSC-RS2=MapaMicrozonificacionSismica.pdf)
Geographic/geomorphic information		
- [REQUIRED] High resolution digital elevation model.	A local DEM model is not available and a new DEM model will be created using SRTM data.	SRTM format
Geological information		
- [REQUIRED] Geological map (with the highest resolution possible and ideally in digital format)	Geological map of Cali (1:20 000 scale). Surficial geological units map of Cali (1:20 000 scale).	PDF format (MZSC-G1=Geologia.pdf) PDF format (MZSC-G2=UnidadesGeologicasSuperficiales.pdf)
- [optional] Geomorphological map (with the highest resolution possible and ideally in digital format)	Geomorphological units map of Cali (1:20 000 scale).	PDF format (MZSC-G3=UnidadesGeomorphologicas.pdf)
- [optional] 3-dimensional geological models (e.g. models that describe shape and materials filling a sedimentary basin)	Not available	
- [REQUIRED] Borehole stratigraphies (ideally in digital format)	Tables with lithostratigraphic description of boreholes	PDF format (ANEXO GT2 DESCRIPCION LITOLOGICA.pdf)
Geotechnical information		
- [REQUIRED] If shear-wave velocity profiles are not available, CPT and SPT profiles	Geotechnical profiles with donwholes information, including Vs	PDF format (ANEXO GT4 PERFILES GEOTECNICOS MZSC.pdf)
- [optional] Shear modulus and damping Vs. strain curves	Plots	PDF format (See figures in Informe 4 Geotecnia.pdf)
Geophysical information		
- [REQUIRED] Shear-wave velocity profiles (from downholes, MASW, SASW)	Vs profiles are included in the geotechnical profiles	PDF format (ANEXO GT4 PERFILES GEOTECNICOS MZSC.pdf)

- [optional] Results of seismic refraction surveys	Cross sections from seismic reflexion	PDF format (See figures in Informe 3 Geofisica.pdf)
- [optional] Results of geophysical surveys	Cross sections from gravity and geoelectricy	PDF format (See figures in Informe 3 Geofisica.pdf)
- [optional] Results of microtremor measurements	Map of isoperiods from microtremor measurements	PDF format (MZSC-RS1-MapaIsoperiodosMicrotrepidacionesCali.pdf)
Seismological information		
- [optional] Weak-motion recordings collected by dense-seismic networks (typically for local site-response analysis)	Not available	
- [REQUIRED] Strong-motion recordings (these will be used to perform 1D ground response analysis) + information on strong-motion stations	Records from SARA project	GMPE-SMTK format

3.2 Quito city, Ecuador

Quito is the capital of Ecuador and its administrative and political center. The city is located on the Ecuadorian Andes, at an altitude of 2800 meters, covering an area of about 290 km^2 with an elongated shape in the NS direction. The city lies within the Interandean Depression (ID), in a basin limited by the Western (WC) and the Eastern (EC) Cordilleras. The city is affected by earthquakes occurring in the ID valley, experienced macroseismic intensities larger than MMI 6 on more than 20 times in the 486 years of its history.

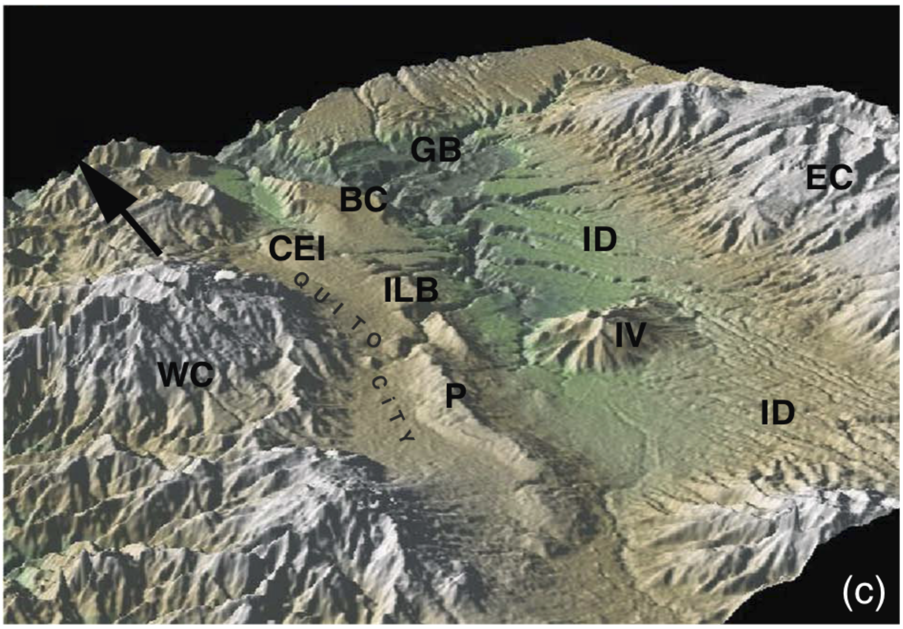


Figure 23. 3D view of Quito basin in the Interandean Depression (ID). WC: Western Cordillera, EC: Eastern Cordillera. BC, P, ILB and CEI: Hills around Quito. The DEM was created using SRTM data. Source: Alvarado et al. (2014).

According with several studies, Quito have developed in a piggy-back basin on the hanging wall of a reverse fault system. The activity of this fault system has been recognized by historical, geomorphologic, geologic, and geodetic studies (Egred, 2009; Champenois et al., 2013; Alvarado et al., 2014).

3.2.1 Previous information

Quito is one of the most studied cities regarding seismic hazard, seismic microzoning and risk in South America. The microzonation studies started in the 90s in the framework of the Earthquake risk management pilot project of Quito (EPN, 1995, Chatelain et al., 1996), where a group of local and international experts worked together to identify the sources producing damaging (scenario) earthquakes on the city. In this project, the first microzonation of the city, based mainly on topography, surface geology, seismic refraction analysis, electrical prospecting data and lithostratigraphic characterization of soils in the first 20-25 meters, was obtained (see Figure 24).

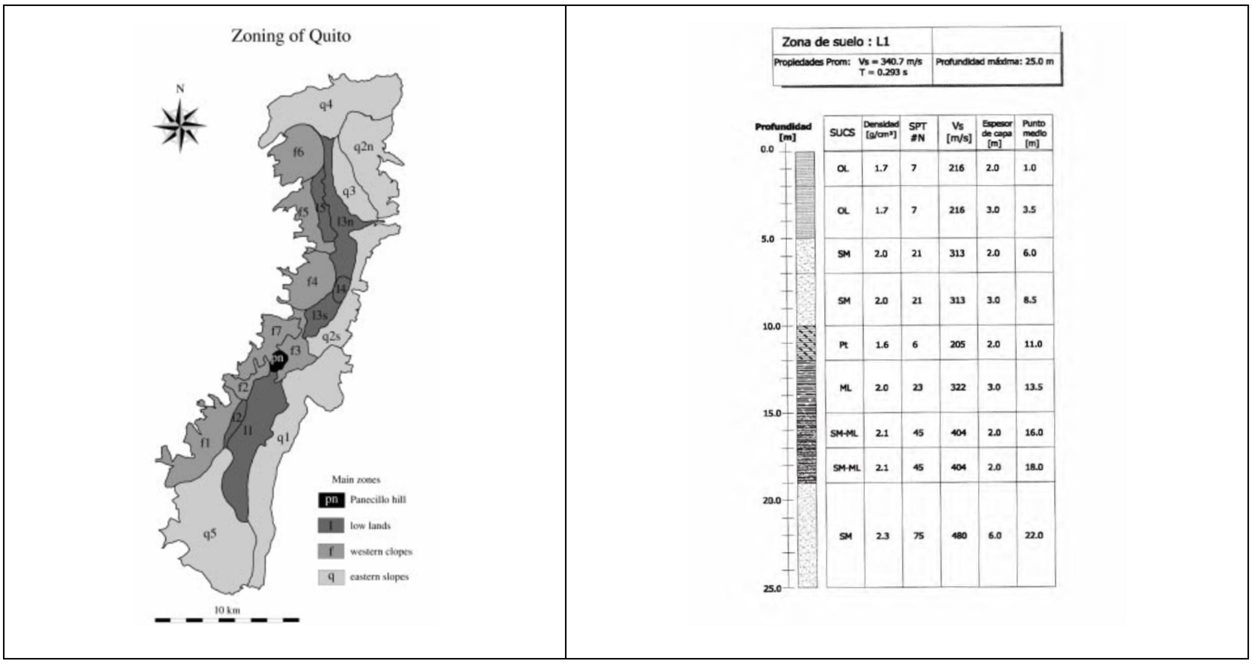


Figure 24. Microzonation zoning of Quito from EPN (1995). In the right panel: main characteristics of the soil profile L1. Source: EPN (1995) and Chatelain et al. (1999).

In 2002, Valverde et al. (2002) from EPN (Escuela Politecnica Nacional) produced a new microzonation map (see Figure 27) using information from EPN (1995) and additional data from geophysical (i.e. microtremors, downhole), geotechnical (i.e. CPTN), investigations, laboratory analysis, and response analysis modelling using Shake91 (Schnabel et al al. 1972). The zonation proposed was based on the soil classification used in the Ecuadorian building code (CEC-2000), which divide the soil into four classes (S1: rock of stiff soil with VS > 750 m/s, S2: stiff soil, S3: soft soil, and S4: very soft soil). For each zone a design spectrum, transfer functions and the fundamental period of vibration of the soil were provided.

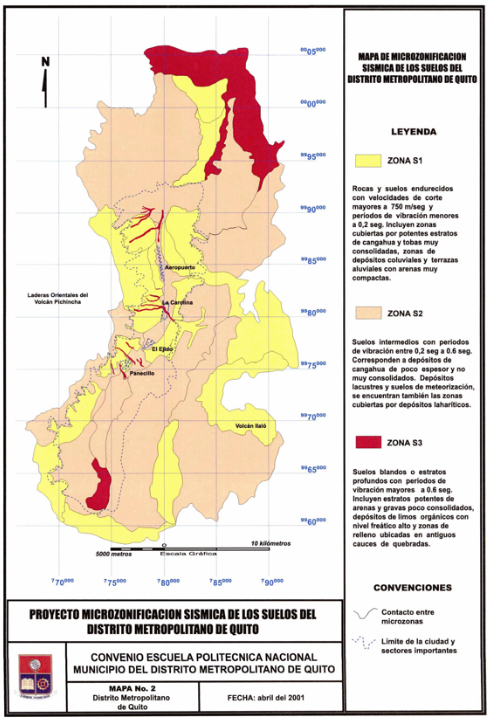


Figure 27. Microzonation zoning of Quito from Valverde et al. (2000). Source: Valverde et al. (2000).

More recently, in 2012, a consortium led by ERN (Evaluación de Riesgos Naturales, ERN, 2012) performed a new microzonation study for Quito. In this project, a seismic hazard model for Ecuador, including sources affecting the city, was developed. New geophysical and geotechnical investigations were performed and additional information from the METRO project (TRX-Consulting C.A, 2011) was used. The main results of the project were: a microzonation map with 13 zones, amplification site factors (Fa, Fd and Fs) according with the Ecuadorian building code (NEC-11) and rock and soil hazard maps for several return periods (55, 225, 475, 1000 and 2500 years). In Figure 3.13 the spatial distribution of the site factor is presented.

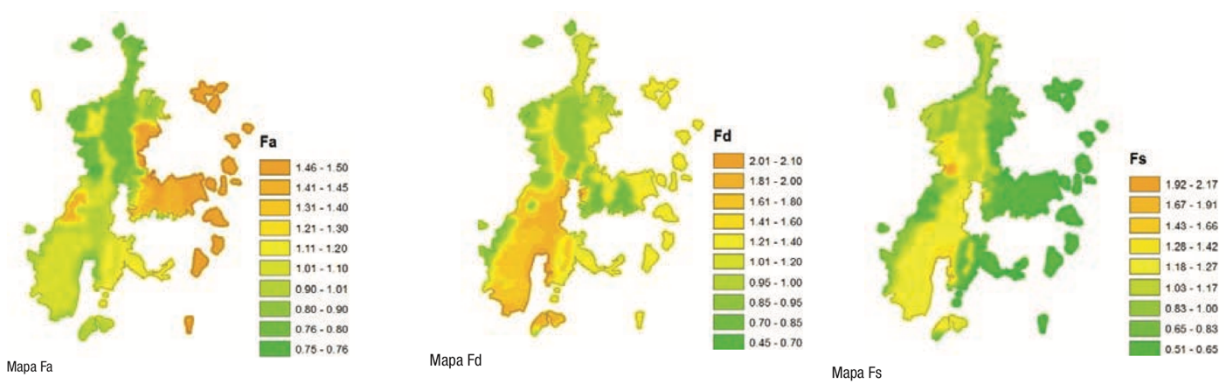


Figure 28. Site amplification factors distribution for Quito from ERN (2012). Source: ERN (2012).

Aguiar (2017) from ESPE (Universidad de las Fuerzas Armadas) performed a new microzonation study for Quito. The novelty in this study is the consideration of the blind reverse faults below the city as potential scenarios and the computation of response spectra using these faults and a maximum characteristic earthquake (MCE) model. In this study a new classification of the soil is proposed, based on the Ecuatorian building code (NEC-15, Figure 29). Aguiar (2017) suggests to use the site amplification factors proposed by ERN (2012) but following the new NEC-15 formulations.

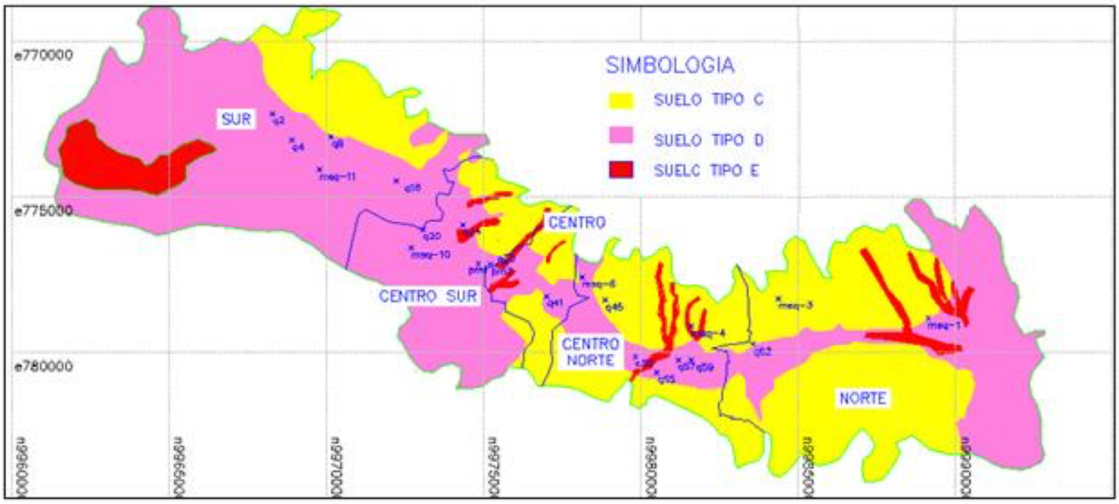


Figure 29. Microzonation zoning of Quito from Aguiar (2017). Source: Aguiar (2017).

3.2.2 Geological and geomorphological information

Quito is built on Plio-Quaternary volcanoclastic basins in the Interandean Depression (ID) and between the Western and the Eastern Cordilleras (Winkler et al. 2005). The city is surrounded by three hanging sub-basins: the Machangara, El Batan and San Antonio Basin, which contain Quaternary volcanoclastic sediments. The simplified geological map of Quito (1:50000 scale) presented in Figure 28 was created by ERN (2012).

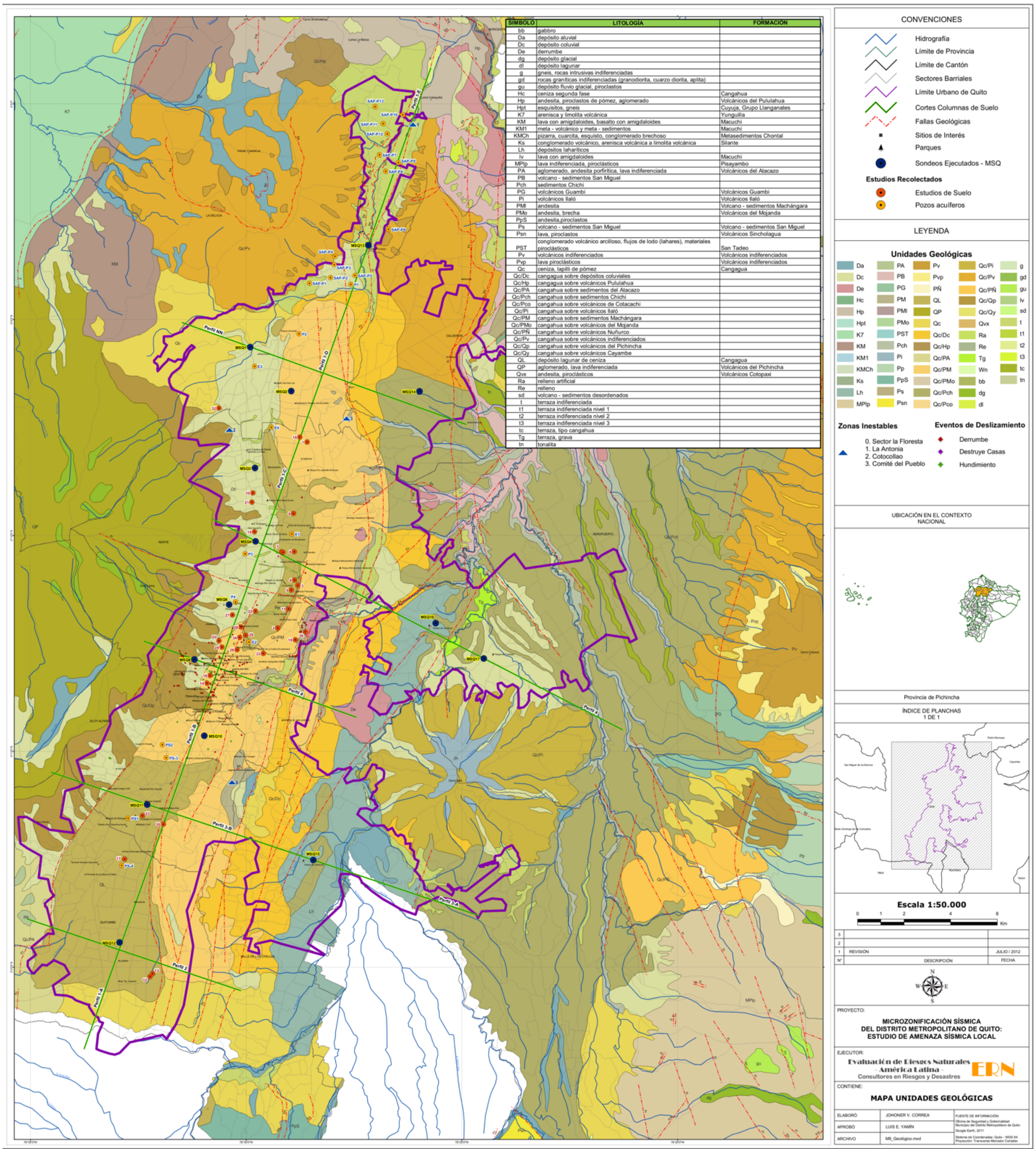


Figure 30. Geological map of Quito. Source: ERN (2012)

The sedimentary sequences range between latest Miocene and Pleistocene. The sedimentary sequences overlie the basements rocks of the Cordilleras (basaltic rocks of the Cretaceous Palatanga unit or Pliocene volcanic rocks of the Pisque Formation) as well as the Oligocene-late Miocene volcanic successions. Figure 31 presents the simplified stratigraphic columns for the Quito and the ID basins according with Alvarado (1996).

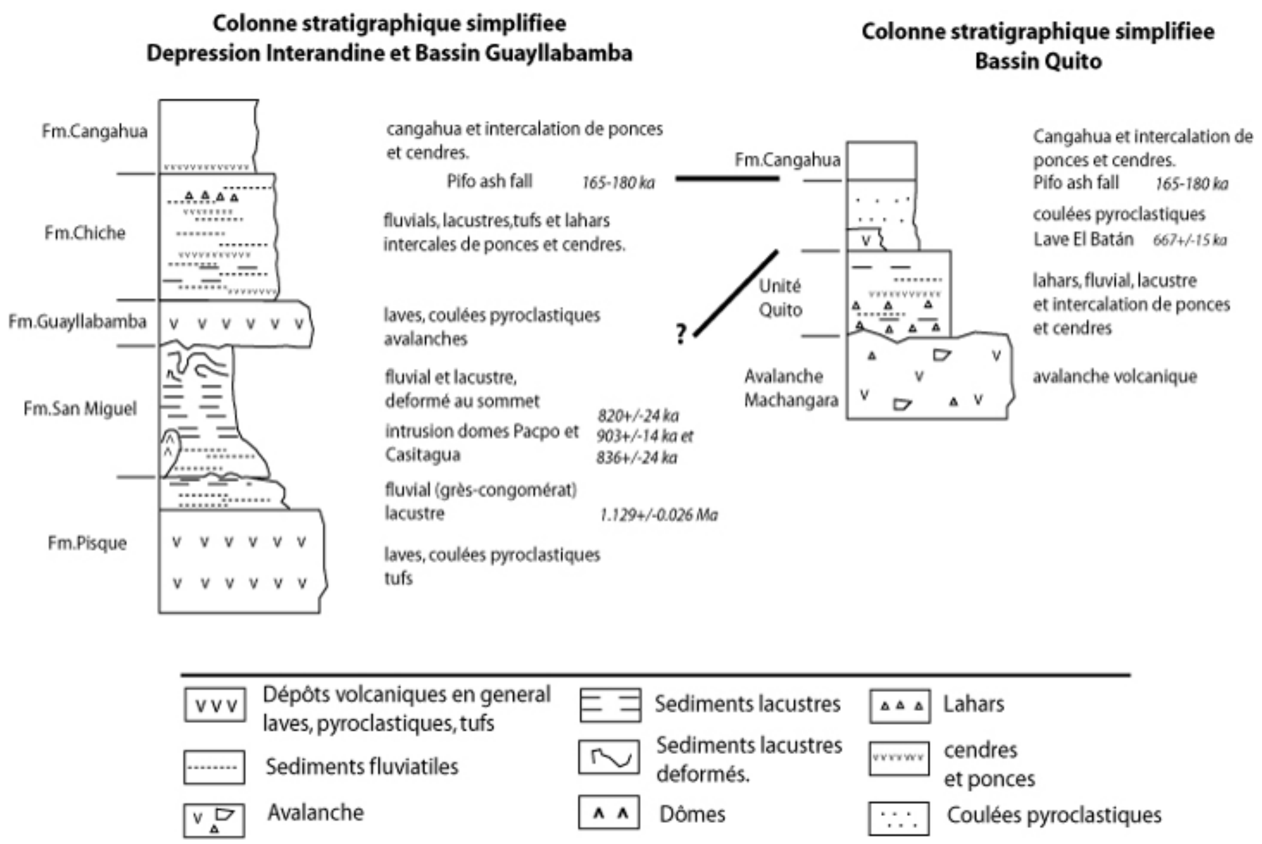


Figure 31. Simplified stratigraphic columns for Quito and Guayllabamba basins. Source: Alvarado (1996).

3.2.3 Geophysical information

As was explained in section 3.3.1, several and different geophysical investigations have been carried out during the microzonation studies performed for Quito in the last 25 years. Seismic refraction, cross-hole, borehole and recently refraction microtremor (ReMi, Louie, 2001) investigations have been used to determine the dynamic characteristic of the soil on depth and the spatial distribution of sites with similar characteristic on the city. Several studies provided simplified cross-sections with information about thickness of soil strata, materials, density, velocities, and/or geotechnical parameters. Usually, the results obtained in a previous study were integrated in the newer ones and re-interpreted following the specifications of the current building code. Simplified cross-sections describing the structure of the Quito basin on depth were provided from ERN (2012).

3.2.4 Geotechnical information

As for Cali, a Database of Geotechnical Data is not available for Quito. Then, also in this case, the geotechnical information available can only be founded in the microzonation studies developed for this city. From our perspective, ERN (2012) and Leon (2018) contain the most complete geotechnical information.

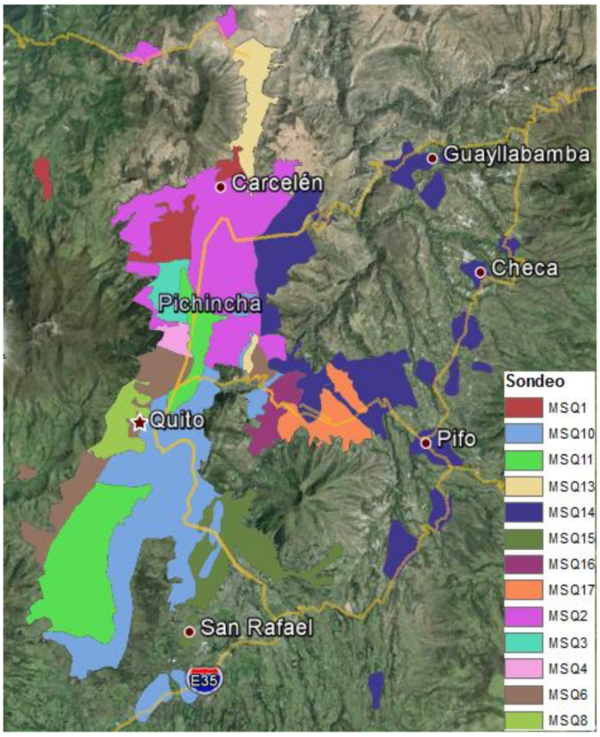


Figure 32. Microzonation zoning of Quito from ERN (2012). Source: ERN (2012)

ERN (2012) provides a zonation with 13 zones (see Figure 32) describing geologic, lithostratigraphic, geotechnical and dynamic characteristics of the soils in Quito. This information was reviewed by Leon (2018) and integrated with new data (i.e. ReMi). A new zonation, presented in Figure 33, is proposed as well as its representative cross-sections.

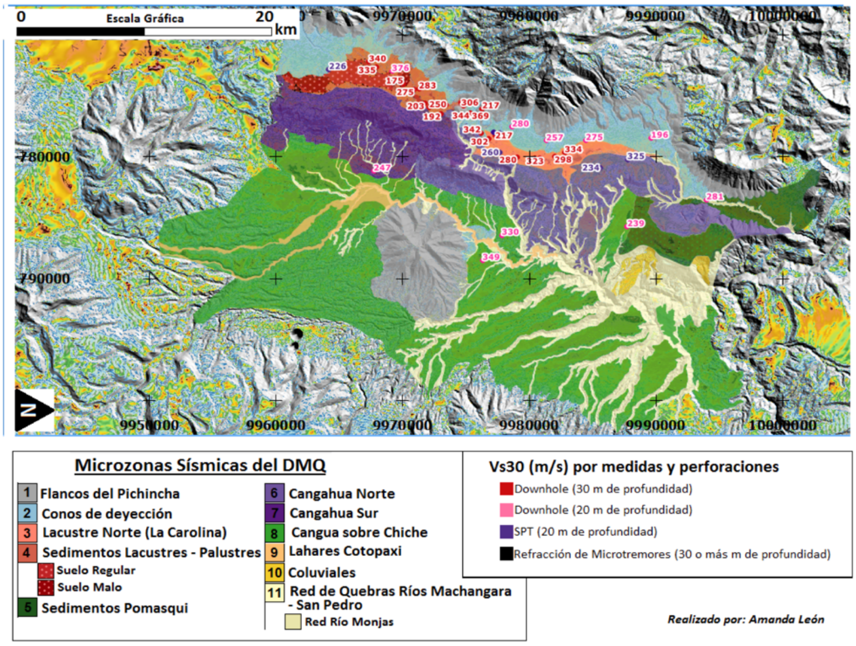


Figure 33. Microzonation zoning of Quito from Leon (2018). Source: Leon (2018)

3.2.5 Summary

In the table below a summary of the data compiled for Quito and the available formats.

HAZARD INPUT DATA		
	Object	Format
Previous information		
- [REQUIRED] Reference to any previous site-response and microzonation study, including datasets and results collected	ERN (2012). "Microzonificación Sísmica Del Distrito Metropolitano De Quito: Estudio De La Amenaza Sísmica A Nivel Local"	Microzonation study for Quito performed by ERN consortiom. It includes a report (pdf format) and tematic maps (in ESRI and PDF format).
	Microzonation map of Quito.	ESRI format (microzonificacion2012.shp) PDF format (MAPA_38_Fa_1.pdf, MAPA_39_Fd_1.pdf, MAPA_40_Fs_1.pdf)
	Transfer functions	PDF format (ANEXO 5 – Anexo 9- Funciones de Transferencia Activa y Subducción.pdf)
	(Falconi, 2017) "Microzonificación Sísmica De Quito"	Extensive review of past microzonation studies for Quito.It proposed a modified version of the ERN(2012) microzonation.
	(Leon, 2018). "Generacion De Mapas Vs30 Y Microzonas Sismicas En El Distrito Metropolitano De Quito, Ecuador"	MS Thesis; proposed a new microzonation map, using new and adjusted Vs values. PDF format (Figure 4.44 in Leon A_2017_Vs30 DMQ y microzonas sismicas.pdf)
Geographic/geomorphic information		
- [REQUIRED] High resolution digital elevation model.	DEM for Quito District	TIFF format (DMQ_17S_hs.tif)

Geological information		
- [REQUIRED] Geological map (with the highest resolution possible and ideally in digital format)	Geological map of Quito (1:50 000 scale).	ESRI format (GeologiaDMQ.shp) PDF format (MAPA_9_Geologico_Esc50000_1.pdf)
- [optional] Geomorphological map (with the highest resolution possible and ideally in digital format)	Geomorphological map of Quito (1:50 000 scale).	PDF format (MAPA_10_Geomorfologico_Esc50000_1.pdf)
- [optional] 3-dimensional geological models (e.g. models that describe shape and materials filling a sedimentary basin)	Not available	
- [REQUIRED] Borehole stratigraphies (ideally in digital format)	Figures with lithostratigraphic description of boreholes	PDF format (ANEXO 4 – Sondeos y estudios de Suelos.pdf)
Geotechnical information		
- [REQUIRED] If shear-wave velocity profiles are not available, CPT and SPT profiles	Geotechnical profiles with donwholes information, including Vs	PDF format (ANEXO 5 – Perfiles Estratigraficos Sondeos de la Microzonifica.pdf) PDF format (ANEXO 8 – Perfiles Estratigraficos Sondeos del Estudio Metro.pdf)
- [optional] Shear modulus and damping Vs. strain curves	Plots	PDF format (Figure 4.7 and Anexo 6-Resultados Ensayos de Laboratorio para cada Sondeo_2)
Geophysical information		
- [REQUIRED] Shear-wave velocity profiles (from downholes, MASW, SASW)	Vs profiles included in the geotechnical profiles	PDF format (ANEXO 5 – Perfiles Estratigraficos Sondeos de la Microzonifica.pdf) PDF format (ANEXO 8 – Perfiles Estratigraficos Sondeos del Estudio Metro.pdf)
- [optional] Results of seismic refraction surveys	Not available	
- [optional] Results of geophysical surveys	Simplified cross sections	PDF format (Figures 3.2 – 3.7 in microzonation report)
- [optional] Results of microtremor measurements	Not available	
Seismological information		
- [optional] Weak-motion recordings collected by dense-seismic networks	Not available	

(typically for local site-response analysis)		
- [REQUIRED] Strong-motion recordings (these will be used to perform 1D ground response analysis) + information on strong-motion stations	Records from SARA project	GMPE-SMTK format

3.3 Santiago de los Caballeros city, Dominican Republic

Santiago de los Caballeros city is located in the Cibao Valley in the Dominican Republic. Santiago de los Caballeros is the second largest city of this country and the major socio-economic and industrial metropolis in the north-central part of the Dominican Republic.

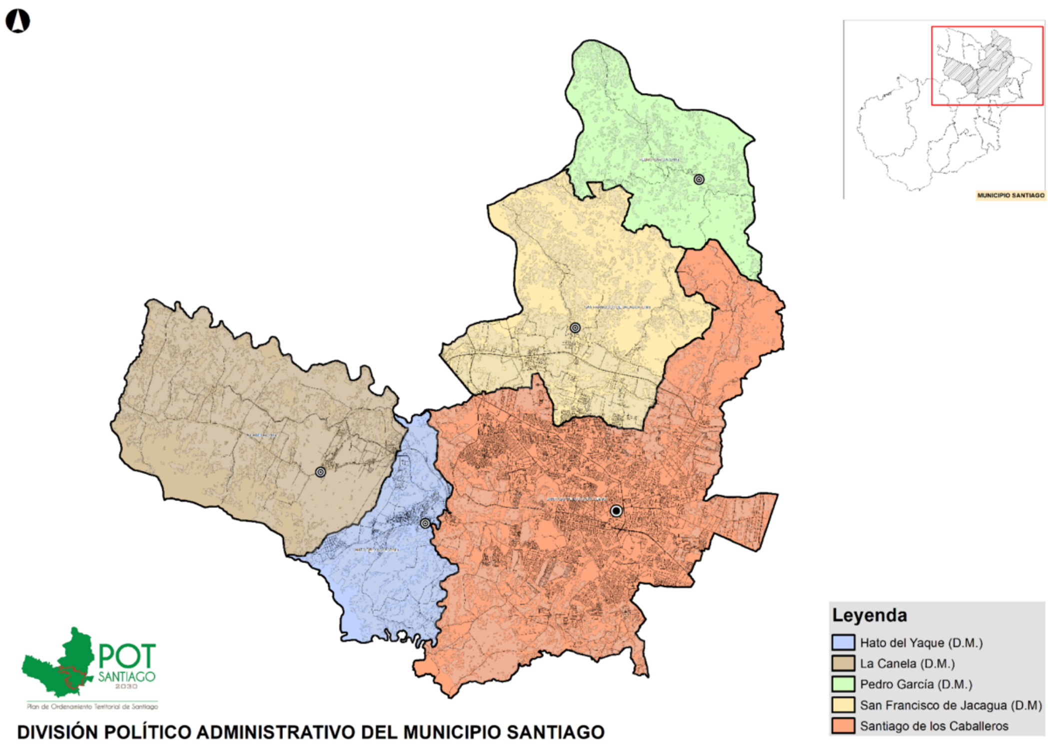


Figure 34. The Santiago de los Caballeros municipality. Source: PMOT Santiago (2017-20130)

3.3.1 Previous information

After the tremendous disaster caused by the 2010 M7.1 Haiti earthquake, the evaluation of seismic hazard in the Dominican Republic became an urgent priority issue for the Dominican Republic government and the scientific community. In response to this, between 2011 and 2016, the governments of Haiti and the Dominican Republic started a collaboration program with the Bureau de Recherches Géologiques et Minières (BRGM) of France to develop microzonation studies in both countries. In the Dominican Republic two cities were selected: Santo Domingo and Santiago de los Caballeros. The Santiago de los Caballeros project financed by European funds started in 2010 and the activities were divided in two main topics:

b) hazard assessment for rock condition for PGA and exceedance probabilities of 10% and 2% in 50 years, and
c) microzonation study for the urban part of the city.

The seismic hazard assessment study was developed by BRGM in collaboration with local experts from the Servicio Geológico Nacional (SGN) of the Dominican Republic. In the internal report provided by SGN (Bertil et al.,2011), the authors recognised that the Septentrional Fault is the major contributor of hazard for the Santiago de los Caballeros city due to its proximity to this major seismogenic fault source (< 10 km).

The microzonation study (Roullé et al. 2011; Llorente et al. 2017) was developed in close collaboration with the Instituto Geológico y Minero de España (IGME). Geological investigations were performed and a new geologic map for the region was created. To characterize the properties of the surficial deposits, geotechnical borehole data (i.e. SPT) and laboratory tests were collected. In addition, geophysical campaigns were executed to determinate the main characteristics of the geological units (i.e. thickness, shear wave velocity Vs, fundamental period). Two techniques were used:

a) The Horizontal-to-Vertical Spectral Ratio (HVSR), based on ambient-noise measurements, and
b) The Spectral Analysis of Surface Waves (SASW), based on seismic prospecting.

The integration of the geological, geotechnical and the geophysical data allowed the delimitation of zones, each of them described by a representative soil column. The zonation obtained for Santiago de los Caballeros, containing seven zones, is presented in Figure 33. A design spectrum based on adapted amplification coefficients (Fa and Fv) was computed using equivalent-linear analysis for only five zones. Two zones need further investigations or a different approach since the results obtained revealed high discrepancies among information obtained using different techniques. The design spectra were computed using CyberQuake and time series and the dynamic soil properties selected from literature.

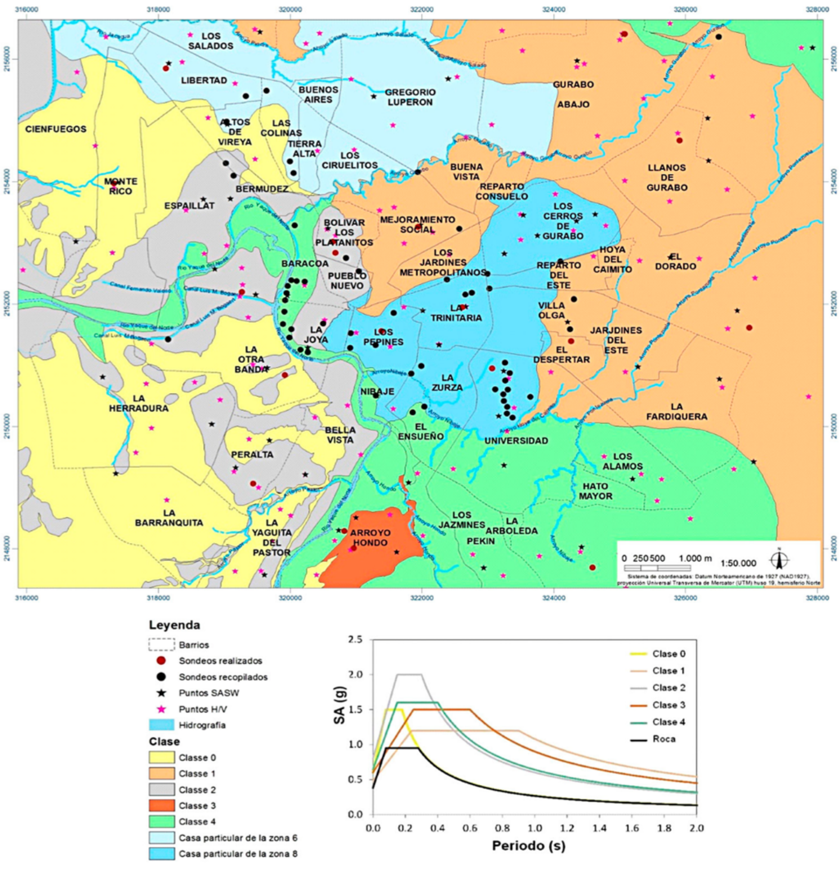


Figure 35. Microzonation zoning of Santiago de los Caballeros from Roullé et al. (2011). Source: Llorente et al. (2017)

3.3.2 Geological and geomorphological information

The geologic map (with representative cross-sections) is presented in Figure 36. In the Santiago de los Caballeros region, according with Llorente et al. (2017), three major litho-geological groups can be identified: materials belonging to the Septentrional Cordillera, Neogene units from the Cibao Valley and Quaternary deposits.

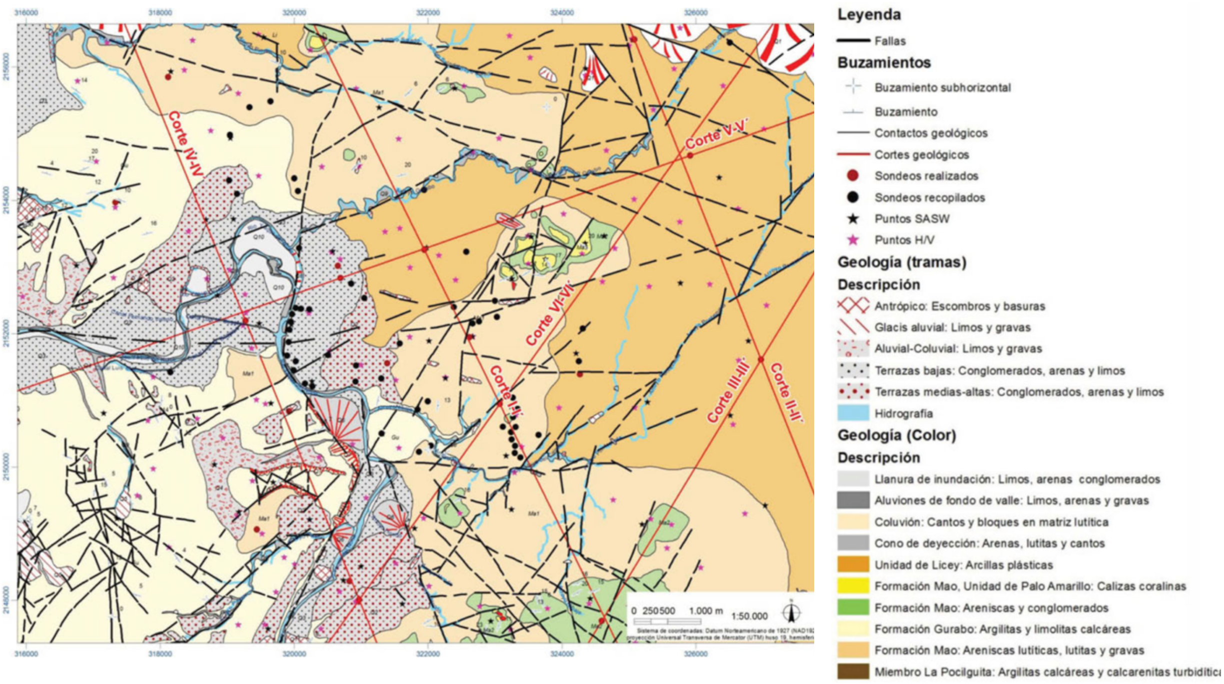


Figure 36. Geological map of the Santiago de los Caballeros. Source: Llorente et al. (2017)

The Septentrional Cordillera materials are present only in a small area at NE of the map. The Cibao Valley materials cover a major part of the study area. To this group belong the Bulla, Cercado, Gurabo and Mao units. These units from the early Miocene – Pleistocene are composed mainly by two lithologies: calcareous siltstone facies and reefal limestones facies. The calcareous siltstone facies dominate outcrops in the Santiago de los Caballeros region, but close to the city, the lower Gurabo-age strata is comprised of the reefal limestones facies. The Mao formation (early to late Pliocene) is composed by conglomerate, sandstones and limestones. In the geologic map, this formation has been sub-divided in three units: a) sandstones with intercalations of lutites and shales, b) conglomerates and medium grain sandstones in deltaic sequences and c) limestones with intercalations of loams. The Quaternary deposits lie along the axis of the valley and can be identified in the alluvial fans located in the piedmont of the Septentrional Cordillera and the Licey Unit.

3.3.3 Geophysical information

As was explained before, two geophysical campaigns were performed during the microzonation study in order to determine the thickness and the share wave velocities of the strata below Santiago de los Caballeros area. This information is crucial for the site response numerical simulations. Two techniques were used:

a) The Horizontal-to-Vertical Spectral Ratio (HVSR), based on ambient-noise measurements, and
b) The Spectral Analysis of Surface Waves (SASW), based on seismic prospecting.

The HVSR measurements were carried out in 147 selected sites and 56 SASW profiles were also performed. In Figure 37 the spatial distribution of HVSR and SASW results are presented. The HVSR results indicate the fundamental frequency measured in the site, while for the SASW results the share wave velocity in the first 30 meters (Vs30) was computed. The Vs profiles are included in the Annex III of the Roullé et al. (2001).

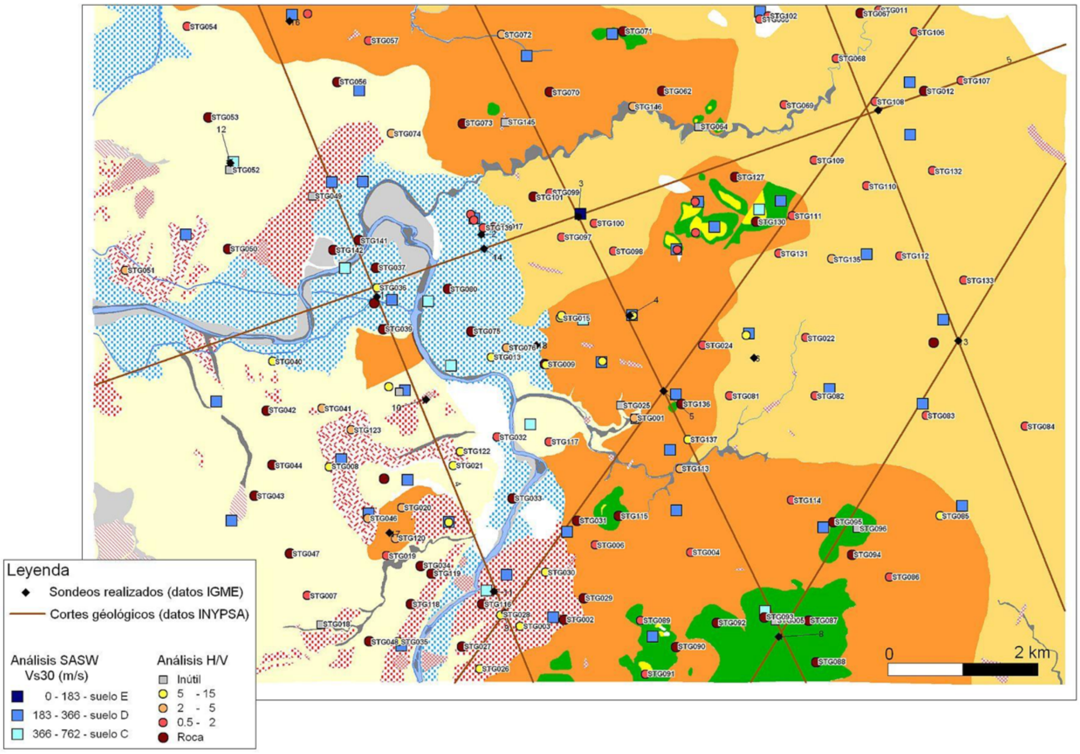


Figure 37. Results of the HVRS and SASW campaigns for the Santiago de los Caballeros city. Source: Roullé et al. (2011)

3.3.4 Geotechnical information

The geotechnical data available for the city come from an older compilation of 54 boreholes with SPT data, published by Penson (1973). The borehole average depth is not optimal (< 10 meters). The lithology is described every 30 cm of thickness and the strata have a limited characterization from a dynamic and mechanical point of view. For this reason, a complementary geotechnical campaign was needed, and 18 new boreholes and laboratory tests were performed by IGME (2010).

The combination of the geological, geotechnical, and geophysical data allowed the creation of a first zonation, describing 10 zones of similar litho-geotechnical and seismic behaviour. The number of zones was reduced during the numerical site response simulations (see details in 3.4.1 section).

3.3.5 Summary

In the table below a summary of the data compiled for Santiago de los Caballeros city and the available formats.

HAZARD INPUT DATA		
	Object	Format
Previous information		
- [REQUIRED] Reference to any previous site-response and microzonation study, including datasets and results collected	Roullé et al. (2011): Microzonificación sísmica de Santiago de los Caballeros – Republica Dominicana. Amenaza sísmica local. Informe BRGM/ RC-59685-FR, 103 p. Microzonation map of Santiago de los Caballeros (1:10 000 scale).	Microzonation study for Santiago de los Caballeros performed by a consortium of SGN, BGRM and IGME. It includes several reports, figures and maps (in PDF and ESRI format). PDF format (Amplificacion10k.pdf) ESRI format (Amplificacion_Sismica_Local.shp)
Geographic/geomorphic information		
- [REQUIRED] High resolution digital elevation model.	Elevation countours for Santiago de los Caballeros	ESRI format (curvas_sec_nad27.shp)
Geological information		
- [REQUIRED] Geological map (with the highest resolution possible and ideally in digital format)	Geological map of Santiago de los Caballeros (1:10 000 scale).	PDF format (Geologico10k.pdf) ESRI format (several shp layers stored in Geologia folder)
- [optional] Geomorphological map (with the highest resolution possible and ideally in digital format)	Geomorphological units map of Santiago de los Caballeros (1:20 000 scale).	ESRI format (several shp layers stored in Santiago_6074_geomoforlogico folder)
- [optional] 3-dimensional geological models (e.g. models that describe shape and materials filling a sedimentary basin)	Not available	
- [REQUIRED] Borehole stratigraphies (ideally in digital format)	Simplified cross-sections Boreholes	PDF format (08-ANEXO III-Estudio de amplificacion sismica.pdf and cortes_geol_santiago forlder) PDF Format (Figures in 04-ANEXO Ib-Testificacion de sondeos.pdf)

	Maps	ESRI format (several shp layers stored in Geotecnia folder)
Geotechnical information		
- [REQUIRED] If shear-wave velocity profiles are not available, CPT and SPT profiles	Geotechnical profiles with donwhole information (Vs information not included)	PDF format (Figures in 04-ANEXO Ib-Testificacion de sondeos.pdf)
- [optional] Shear modulus and damping Vs. strain curves	Not available	
Geophysical information		
- [REQUIRED] Shear-wave velocity profiles (from downholes, MASW, SASW)	Vs profiles from SASW	PDF format (08-ANEXO III-Estudio de amplificacion sismica)
- [optional] Results of seismic refraction surveys	Not available	
- [optional] Results of geophysical surveys	Not available	
- [optional] Results of microtremor measurements	Not available	
Seismological information		
- [optional] Weak-motion recordings collected by dense-seismic networks (typically for local site-response analysis)	Not available	
- [REQUIRED] Strong-motion recordings (these will be used to perform 1D ground response analysis) + information on strong-motion stations	Not available	

4 CONCLUSIONS

To assess seismic hazard at an urban scale in the framework of TREQ, the most recent national models available for Colombia and Ecuador have been selected. The selection of the NSHM reference models was based on the state-of-the-art of modern regional and national PSHA models (Gerstenberger et al., 2020) and the principles and concepts that should be considered during the creation of a PSHA model proposed in Pagani et al. (2015).

For Colombia, the SGC-GEM (2018) model was selected, while for Ecuador, the Beauval et al. (2018) was preferred. Both models fulfil the requirements described in section 2.2 and can be used to compute hazard at bedrock for the selected cities.

For Ecuador, the authors decided not to share with TREQ the full model, but only a branch allowing similar seismic hazard results for Quito than using the full model.

For the Dominican Republic, a national model using as a backbone the last version of the GEM regional hazard model for the Central America and the Caribbean will be developed. The new NSHM model will be completed in close collaboration with local organizations.

Regarding the compilation of available datasets for the selected cities, detailed geological, geotechnical and geophysical information and data were provided by local organizations collaborating with TREQ. The major contribution comes from microzonation studies carried out in the selected cities. The amount and quality of this information varies depending on the city. For instance, Quito is the most studied city. In the case of Santiago de los Caballeros, even though the amount of shared information is large, its quality is lower. For the three cities, often the provided data are not in digital format and further effort will be needed to use it in the project.

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