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Site Characterization for Strong Motion Stations in Latin American Countries

R. Boroschek(1), A. Giuliano(2), H. Garcia(3), V. Schmidt(4), A. Climent(5), JC Singaucho(6), C Viracucha(6), R. Torres(7), L. Alcantara(8), E. Talavera(9), H. Tavera(10), F. Lazares(11), H. Rendón(12), V. Rocabado(12), M. Schmitz(12),

(1) RENADIC, Department of Civil Engineering, University of Chile, Chile, rborosch@ing.uchile.cl
(2) INPRES, Argentina, giuliano@inpres.gov.ar
(3) Colombian Geological Service, Accelerograph National Network, Colombia, hgarcia@sgc.gov.co
(4) Director, Earthquake Engineering Laboratory University of Costa Rica, Costa Rica
(5) Costa Rican Electrical Institute, acliment@ice.go.cr
(6) Geophysical Institute, National Polytechnic University, Ecuador, jcsingaucho@igepn.edu.ec
(7) Environmental Observatory, Ministry of Environment and Natural Resources, El Salvador, rtorres@marn.gob.sv
(8) Engineering Institute, UNAM, Mexico,LAlcantaraN@iingen.unam.mx
(9) INETER, Nicaragua, emilio.talavera@gf.ineter.gob.ni
(10) Geophysical Institute of Peru, Peru, hernando.tavera@igp.gob.pe
(11) CISMID, Peru, f_lazares@uni.edu.pe
(12) FUNVISIS, Venezuela, hrendon.funvisis@gmail.com

Abstract

The geotechnical characteristics of a site for a strong motion station have a substantial bearing on understanding the recorded data and its usefulness. Latin American countries, with very limited budgets for strong motion monitoring, have reluctantly restricted their site evaluations to simple visual inspections and, in general, to noninvasive techniques—intensive soil explorations are rare. This article presents a summary of the methodology used in Argentina, Chile, Costa Rica, Colombia, Ecuador, El Salvador, Mexico, Nicaragua, Panama, Peru and Venezuela. Most of the above countries apply similar procedures. Initial site selection criteria considered for a new strong motion instrument station are typically based on the site's ease of instrumentation, followed by population density, the area's economic importance, instrument safety and communication accessibility. After these considerations have been examined, the seismic site class is evaluated. In general, once the site has been pre-selected, an initial classification is performed based on visual inspections of surface soils, data from exploration of nearby constructions, and available geotechnical and geological maps of the site. For all recording stations, a detailed study is performed only after the station has been installed and, more commonly, after critical data have already been recorded at the station. Most sites are typically characterized using very basic analytical methods such as horizontal-to-vertical-spectral-ratios (MHVSR) as recorded from ambient vibration (microtremor), or EHVSR from small and large amplitude earthquake recordings. A much smaller set of stations has estimations based on noninvasive surface-wave techniques that include the spatial auto-correlation (SPAC) analysis method and/or the multi-spectral analysis of surface waves (MASW) method, and on rare occasions, estimations are based on soil boring exploration with downhole shear wave velocities measurements.

Keywords: strong motion data, site characterization, ambient vibration, geophysical exploration.

1. Introduction

Strong motion recording started in Latin American countries (LAC) in the 1930s, when a C&GS accelerograph was installed in the Balboa Heights Administration Building, Panama in 1934 [Knudson 1978]. Due to reduced budgets and the scarce research community, networks development in Latin-American countries had a slow start and relatively few and sparsely located instruments. Nevertheless, because of high seismicity in the region, relevant records were rapidly produced and they provided important information for the initial understanding of strong shaking. This can be seen in the attenuation studies of the 1960s where, in some studies, LAC data represented 32% of the data set [Cloud and Perez, 1969]. According to Harverson, by 1963 there were 72 accelerographs located in the Americas, of which 7 (9.7%) were located in LAC. By 1974, there were 21 accelerographs in Central America and 81 in South America, [Knudson, 1978].

After the strong support received from USA institutions in the 1930s and 1940s, the scarcely distributed instruments faced serious difficulties due to poor maintenance programs. A stronger development of the network started in 1970 and finally in the 2010s.

2. Network Characteristics and Soil Characterization

A short description of the network is presented for each of countries reported.

2.1 Argentina

The only national accelerograph network in Argentina is managed by the National Institute for Seismic Prevention (INPRES). It is a strong motion network consisting of 113 accelerographs. The network started operating in 1970 and the first record was obtained during the 1977 Caucete Ms =7.5 earthquake. Other important records were obtained in the 1985 Mendoza Mw=6.0 earthquake, the 2002 Mw=6.0 La Rioja earthquake, the 2004 Catamarca Mw=6.4 earthquake and the Salta 2010 Mw=6.3 earthquake.

Instrument location is shown in Figure 2. Sites are selected based on seismicity and population density. Soil type is not a decision variable for selecting station location. There are no standard station types and, in general, accelerographs are installed inside an existing structure and anchored to the slab foundations. At present, no special evaluation is performed on soil or topography conditions.

The number of units is equivalent to 0.4 accelerographs per 10.000 km2 but most of the country is not seismic. In high seismicity areas, there is an average of 3.75 units per 10.000 km2.

Also, there is a local strong motion network managed by the National Technology University located in Mendoza.

2.2 Chile

Chile started its strong motion monitoring in the 1940s. The first accelerograph was installed in 1944 on the Campus of the School of Engineering, University of Chile. In 1950, a Japanese SMAC was also installed there [Knudson, 1978]. The first earthquake recorded was in September 13, 1945 Ms=7.1. The record was obtained with a Montana accelerograph located in Santiago. It recorded a peak ground acceleration of 0.15g. Other records were obtained later, with a small set of data. Because of these early recordings and recognizing that Chile is a natural laboratory for monitoring earthquakes, soil and structures, an agreement was signed between the University of California and the University of Chile, with the purpose, among others, to install 57 additional Montana accelerographs. Ten of these instruments were installed in 1967. The criterion for site selection in the 1960s was: that a magnitude 7 or larger should result in no less than one record and that an instrument should be located no more than 200km from a known high seismic source. Priority should be given to installed instruments close to known seismic sources. Instruments should be located on sites with the most common soil type representing the more important structures and, on those sites, close to structures that would provide information on soil-structure interaction [Duke and Leon, 1969].

In the 1970s and 1980s, the most critical dams associated with electric power generation in Chile started to be equipped with instruments. This gave a strong impulse to monitoring. These networks, together with those managed by the University of Chile, recorded the 1985 Mw 7.8 Central Chile earthquake. The data obtained had a huge impact on the national and international community because, at the time, there were few records of this magnitude available. The University of Chile network later recorded the 2001 Mw 8.4 Southern Peru Earthquake, and the 2010 Mw 8.8, the 2014 Mw 8.2 and the 2015 Mw 8.3 Earthquakes.

The modern ground level strong motion network (National Seismological Center (CSN) and Civil Engineering National Accelerograph Network (RENADIC), both operated by the University of Chile) are placed following two global criteria, Figure 3. Approximately 100 accelerographs for seismological studies are located in low noise areas with hard soil conditions, preferably rock. These accelerographs are part of a broad band station equipped with a seismometer, some of them continuous displacement (GPS), and data recording and communication systems. These stations are primarily used for seismic source studies, location, magnitudes, rupture evaluation and others. Additionally, for engineering and response purposes, there are approximately 330 accelerographs located in areas with a population density higher than 50,000 persons, areas of future economic development and areas critical to industrial development. Stations of these networks must be located not more than 50 km apart in order to ensure good spatial coverage (this is not actually always fulfilled) and cover most of the soil type definitions established in Seismic Design Codes. Instrument density is approximately 6 per 10.000km2.

A typical station type for the seismological network consists of burial and sand cover in remote areas. Strong motion stations for engineering purposes consist essentially of two different station types. RENADIC only installs equipment inside existing one story structures. Communication with the equipment is mainly via telephone lines and, in some cases, data must be retrieved manually. The CSN accelerometer network is installed on a concrete foundation that includes a pedestal.

Soil classification for the engineering oriented network is initially based on a visual inspection of superficial soil, knowledge of boring or excavations of nearby construction sites and geological maps. After installation, some sites have been studied using microtremor measurements, typically, H/V ratios. After good information is obtained more detailed investigations have been performed (SPAC, MASW, H/V from Earthquake records). In very few stations, and after very critical information has been obtained, boring with soil testing including downhole seismic testing has been performed, [Boroschek et al 2012].

Topographic characteristics are not considered in the site selection process and no information is included on the site characteristic files.

2.3 Colombia

The first accelerograph (a C&GS accelerograph) was installed in 1945 by the Los Andes Colombianos in Bogota. In 1970, the network was increased with 10 C&GS accelerographs transferred from the Canal Zone.

The National Accelerograph Network of Colombia started operating in 1993. They defines the need for installing accelerographs based on the following criteria: cities with over 100,000 inhabitants located in mid and high seismic areas according to the Colombian Earthquake Construction Ordinance (NSR – 10). Also, the observation of areas with relevant seismic history is considered. Buildings are also equipped with instruments according to the mandatory rules of NSR-10.

The most important record obtained to day is the January 25, 1999 Mw 6.2 Armenia earthquake and the Quetame Mw 5.9 earthquake of 2008.

Siting of strong motion stations is determined according to the seismicity of the area, and the geologic, topographic and political division of the country. Preferred sites are those located on rock and uniform and compacted soils. These stations are located away from cities, major industrial complexes, trees, antennas and buildings. Siting is complex since stations also need appropriate energy and communications, safety and accessibility.

Stations are typically located on small structures that house a concrete pedestal or an anchoring rock.

In 2015, the network consisted of 116 stations. For data retrieval, 70 stations had local extraction and 46 had connectivity to Bogota via satellite communication.

Site characterization is based on the geological setting and a visual exploration of the site, they are classify as rock or soil. Shear velocity Vs30 has been measured in all stations using geophysical methods resulting in 28 rock stations and 88 soil stations. Some sites have performed HQ diameter boring with soil sampling. Topographically the stations are classified as valleys or mountain.

There are other local networks located in Bogota (30 instruments), Medellin, Cali, Bucaramanga and Manizales.

2.4 Costa Rica

The first instrument, a C&GS accelerograph, was installed in the early 1940s at the University of Costa Rica. The first strong motion record was obtained in San Jose during the November 18, 1945 Ms=7.0 earthquake.

There are mainly two national networks: one run by the Earthquake Engineering Laboratory (LIS) and the other managed by the Costa Rican Electricity Institute. There are other locally managed sensors also.

The LIS National Accelerograph Network started operating in 1984 and obtained its first record in 1985. At present, the network consists of 120 instruments, located as shown in Figure 7. This is equal to approximately 2.35 instruments for every 10.000 km2

As far as possible, instruments are placed in difficult access sites, trying to improve the coverage of territory and also in places close to important bridges and buildings. Most accelerographs are placed in the Central Valley where most people and services are concentrated. Basic requirements for installing equipment are availability of electricity and access to internet, as well as being able to place a GPS antenna outside the building. In addition, safety, access to the site, closeness to crustal seismic fault and interest of building owners are criteria considered in choosing new places where new instruments will eventually be installed.

Generally, accelerometers are attached directly to the slab subfloor, properly anchored by bolts in buildings of one or two levels, Figure 1. This condition is considered as “free field”. There are some cases where one story buildings have been built exclusively to place instruments.

To characterize a site, geological and geotechnical maps of the area are first reviewed. Then, techniques such as H/V (Nakamura), FK (frequency-wavenumber) and SPAC (Spatial autocorrelation) and in some cases MASW are applied to estimate the Vs30. With this value, the soil is classified according to the Seismic Code of Costa Rica which proposes 4 soil types: S1, S2, S3 and S4, where S1 and S4 are rock and soft soil, respectively. Available information of NSPT and groundwater exploration boreholes is also reviewed. So far, topographic effects are not taken into account in site characterization since, in most cases, stations are located in valleys.

Data recorded are transmitted in real time via the internet from each instrument to servers at the Computer Centre of the University of Costa Rica, for storing and processing. Subsequently, several backups of the data recorded are created.

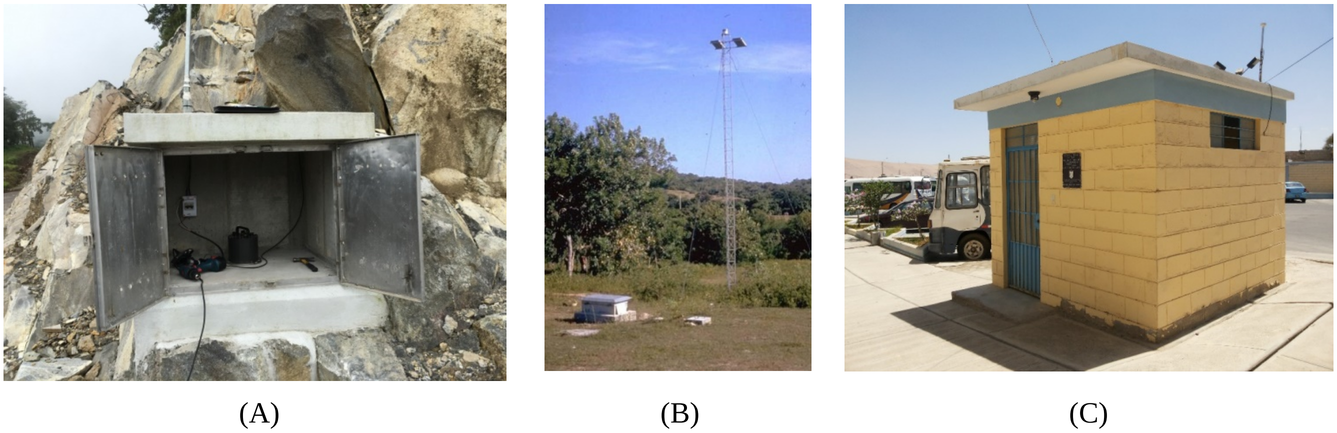
Whenever a moderate or strong earthquake occurs, one of the main products shown on the LIS website is a map of ground motion or shakemap, based on recorded accelerations (PGA). These acceleration values are automatically read from records obtained by more than 100 free field instruments distributed country-wide, specifically located in all provincial main cities and towns.

The other extended network in Costa Rica is managed by the Costa Rican Electricity Institute (ICE). The network started operating in the 1980s mainly to monitor dams. Today the network consists of 31 instruments. They are installed on the dam and surroundings. All stations are located in areas with energy supply and internet connection.

A typical ICE station consists of a concrete pillar anchored to the structure or foundations. The instrument is usually protected by a steel cover and housed in block masonry housing. Data is relayed by fiber optics to the data center in the capital city of San Jose. Data is used domestically and is not distributed.

Sites are characterized geologically and geotechnically using information from the dam construction. Topography is not considered as a station descriptor.

The most important records obtained to date cover the 1990 Mw=6.0 Piedras Negras event, the Limon April 22 1991 Mw=7.1 event, the Parrita November 20, 2004 earthquake, Mw 6.2, the Chinchona January 9, 2009 Mw 6.2 earthquake and the September 5, 2012 Mw 7.6 Samara event.



(A) (B) (C)

Figure 1. - Strong Motion Stations. A) Costa Rica. B) Mexico IINGEN, C) Peru CISMID

2.5 Ecuador

The first strong motion accelerograph (C&GS), was installed at the Quito Astronomical Observatory in 1945 [Knudson, 1978]. In order to understand the behavior of the tectonic environment in Ecuador and mitigate the effects of big earthquakes for the population, the National Institute of Geophysics (IG-EPN) started installing strong motion stations in 2009 under the SENESCYT project. The network started off with 17 accelerometers located in Quito. Nowadays, the RENAC has 116 strong motion sensors from which 60 broadcast in real-time to the IG-EPN. Figure 4 shows the distribution of the stations.

The objectives established when the network was designed were (i) to record soil responses in populated areas and (ii) given that many cities in Ecuador are located close to active faults that generate moderate to strong motion to monitor zones with recognized historical seismicity. RENAC obtained several records during the 2016 Pedernales earthquake and one of the stations (APED) close to the epicenter recorded the largest PGA which was around 1.3 g (uncorrected signal).

Before starting the installation process, a campaign to define the best conditions for the stations was carried out. The general search scheme followed was: (i) For the operation of the electronic equipment, close to electric power supply, avoid closeness to high voltage towers and to ensure transmission, when transmission via radio signal was considered. (ii) for data quality: avoid artificial soil infills, avoid underground ducts (sewage), and avoid the influence of tall buildings.

Stations located in isolated zones (far from populated areas) are installed in reinforced concrete facilities in areas extending over 3 m2. These stations have a velocity sensor, an acceleration sensor and some include a GPS antenna for geodetic measurements (Figure 4). Stations are deployed along the country. Due to the presence of the Andes Mountain range, many stations are located in areas where signals are affected by site effects (e.g. topography and basin effects). To date, the only characterization of sites is based on the H/V technique; however, geophysics campaigns are being carried out to define a Vs30 profile utilizing the MASW procedure.

2.6 El Salvador

The first strong motion accelerograph, a Montana model, was installed by the National Seismological Observatory in late 1964.

Due to the earthquake on March, 3 1965, M=6.0, that caused 125 deaths, three accelerographs were installed in late 1966. The first strong motion records were obtained on November 18, 1967. The most important records were obtained during the earthquake on October 10, 1985 Mw 5.7 (1500 deaths), and the January 13, 2001 Mw=7.7 earthquakes (944 deaths).

Three institutions in El Salvador have strong motion networks: the Ministry of Environment and Natural Resources (MARN), the UCA University and the Rio Lempa Hydroelectrical Commission.

The location of the strong motion stations is not defined by law and it is determined by each institution according to their needs.

Instruments are located in areas where safety and connectivity are guaranteed. Typically, equipment is installed inside one-story structures. Just recently, the accelerograph are install in a special station and anchored to concrete columns of 60 x 30 x 30 cm.

MARN has a total of 42 stations. Twenty of the stations are connected in real time and for 22 stations, data is retrieved manually. This gives a total density of 1 instrument for every 500 km2, but it is not evenly distributed because in San Salvador, there are 20 accelerographs, so there is one every 4 km2, Figure 9.

In general, no geotechnical studies are performed but stations are located so as to avoid volcanic ash soils that could alter motion data.

2.7 Mexico

Deployment of the strong motion network in Mexico started in the early 1960s after the earthquake of July 28, 1957.Two accelerographs were installed in Mexico City: one in the Central Alameda Park and the other in the Latin American Tower. This network was increased considerably starting in the 1980s by UNAM jointly with the University of California, San Diego, when the Guerrero Accelerograph Network was installed. After the 1985 earthquake, several institutions installed and managed networks. In 2000, the Federal Government created the Mexican Seismic Network integrating all local and national seismograph and accelerograph networks. This includes the existing Early Warning network, created in 1991.

The main networks are Engineering Institute of UNAM (IINGEN), Figure 10, National Seismological Service of the Geophysical Institute of UNAM (SSN_IGEOF), The Center for Instrumentation and Seismic Recording (CIRES), Northeast Seismic Network of Mexico, Accelerometer Network of Mexicali, (CICESE) and The Federal Electricity Commission. There are other small accelerometer networks operated in different states of Mexico [Alcantara et all 1999].

The number of free field strong motion accelerographs in Mexico is approximately 400. Thus, the instrument density for the total country is 2 for every 10,000 km2. For high seismic areas (approximately 400,000 km2) this amounts to 10/ 10,000 km2.

Site selection procedures have changed over the years. Initially, sites were selected based on the knowledge of seismic hazard and the occurrence of earthquakes. Most of these stations were initially established on rock sites. The information used to select the sites was regional geology, local topography, noise level and the knowledge that technical personnel had of the surroundings. Basic criteria for selecting a site always included safety and energy supply. Nowadays the National Seismic Network considers, in order of importance: (a) Location to determine more precisely the earthquake location and magnitude and to generate data for a rapid response; (b) Population density; (c) Monitoring of islands and volcanos; (d) Site safety; and (e) Availability of communication and site characteristics.

Station types change considerably depending on network management and local conditions. The most common installation is a concrete base of 1.2 x 0.85 x 0.3 m. For soft soils, additional side walls 1-meter deep are used. The accelerograph is installed on top of the slab, together with the battery and energy system, Figure 1.

Recently a new station type known as Standard Seismic Observatory has been designed. It houses triaxial accelerometers, triaxial seismometers, GPS receivers, digitizers, energy and communication equipment. These stations are typically installed in a small housing of 4.8 x 3.6 by 2.6 m.

Most of the stations are accessed by mobile or conventional telephones. All of them are based on request data by caller. The Early Warning System uses radiofrequency for communication. Just recently, some stations were connected to internet and satellites.

All networks relay their data to their own data centers and to the central system of the Mexican Seismic Network.

Site characterization is done using non-invasive techniques that record microtremors and noise. The natural period of the soil is estimated in addition to determining the stratigraphy and base rock depth. The most common techniques used are H/V ratios and SPAC. Other techniques employed are electrical resistivity, suspension logging and seismic cone. Very few stations have SPT and other types of invasive explorations.

Topographic characterizations are based only on a simple description of whether the area is a valley or a mountain.

Mexico classifies the station as free field, borehole or structure. Free field is classified as such even is it located on a one story structure or close to tall structures.

There is no single data base of strong motion records. Each institution has its own policies for distribution. Nevertheless, the data base from 1961 to 1999 was collected and distributed.

The earthquakes that generated the most important data sets are the ones in 1985 on September, 19 (Mw=8.1) and 21 (Mw=7.6). This data set consisted of 29 triaxial records outside Mexico City and 12 records in the Federal District. Of these records, the stations from the Guerrero Coast, Caleta de Campos (CALE850919), Villita (VILE850919) and Unión (UNIO850919) provided the first records on the epicentral region for this size earthquake and the SCT and CU stations gave an impressive knowledge of the effect of soil amplification. Other critical data sets are Manzanillo, Colima 19951009 (M=8), Puerto Escondido, Oaxaca 19990930 (M=7.5), Tehuacán, Puebla 19990615(M=7) and Mexicali, Baja California 20100404 (M=7.2).

2.7 Nicaragua

The first instruments, AR-240, were installed in1966 with support from the Central Bank of Nicaragua and the National University. Others were acquired by Esso Standard Oil in 1967 and 1968, [Knudson, 1978]. The first important record was the 1972 Managua Earthquake, Mw=6.2.

There is only one national strong motion network managed by the Nicaraguan Institute for Land Studies (INITER). The initial analog network was replaced in 1997 by digital strong motion instruments that transmit data in real time. The network consists of 25 instruments, Figure 8.

Instruments are spatially located to determine event magnitude. Also, a priority is to cover different soil types and critical infrastructure. The selection of the station is based on population density, equipment safety, noise level, real-time communication capacity and also soil type.

There is no special station type. Accelerographs are installed inside existing one story structures. Because of this, all stations are located in cities with intermediate soil types. No special studies are performed to typify soil characteristics. All stations are connected via fiber optic and internet to the central information center.

2.8 Peru

According to Knudson and Perez (1976), the first accelerograph was installed in downtown Lima in 1944 after the May 24, 1940 Mw 8.2 earthquake that damaged the City of Lima and port of Callao. This was the only accelerograph until 1972. The first record obtained was in 1946 but the first process recorded was the 1947 Nov 1 (Husid, 1973). The most important records initially obtained were 1951 Mw~ 6 with maximum acceleration of 0.07 and the October 17, 1966, Ms=7.5 which produced an acceleration of 0.40 g.

Mainly, there are two national strong motion networks. One is managed by the Peruvian Geophysical Institute (IGP) and the other by the Peru – Japan Center for Seismic Research and Disaster Mitigation (CISMID) of the National Engineering University. Just recently, the National Service for the Construction Industry (SENSICO) began installing modern accelerographs in the country.

Today IGP network manages a total of 200 instruments, 44 of those located in Lima, which represent a density of 1.54 instruments per 10.000 km2. Considering the high seismic areas, this density increases to 3.9 instruments per 10.000km2.

The IGP sensors are located based on temporary and long term observation objectives. Most of the stations are located inside structures or close to structures due to problems with vandalism. There has been a strong push to establish rock and soil types but this in not implemented yet. Today, locations are based on station safety and consideration regarding accessibility.

A typical station is a 1 x 1 meter plan pillar, 1.5 meters deep. On top, there is a two-level steel box. The sensor is installed in contact with the foundations. Batteries and electrical systems are located on the second level. No soil characterization has been performed yet and only basic topography is considered.

Data is transmitted by digital radio or internet in the capital city of Lima. For other stations, data is retrieved by hand.

There is no mandatory instrumentation of free field instruments.

The CISMID strong motion network started operating in 1989 and manages the network of SENSICO and National Engineering University (UNI). CISMID has 15 accelerographs: SENSICO has 5 and UNI has 9 instruments, making a total of 29 instruments. Site selection is based on microzonation studies to define the response of different soil types. A typical installation consists of concrete pilasters located inside a masonry housing. Very few stations have soil explorations. The metadata for these stations is not available at this time. Nevertheless, the preferred explorations are small trenches and MASW. All stations are located away from topographical disruptions. The connectivity for this network is via the internet and 3G or 4G cell data base to the main data center.

2.9 Venezuela

The first accelerograph was already installed in Venezuela prior to the 1967 earthquake. After the earthquake, 25 new accelerographs were installed, [Knudson 1978]. The first instrument of the national network managed by FUNVISIS was installed in 1980. The first record was obtained on October 18, 1981 due to the Ms=5.5 event of San Josesito in Tachira State.

After the Cariaco earthquake in 1997, Mw=6.8, the Venezuelan Foundation for Seismological Research, FUNVISIS, took a major step forward to increase, for the country, the capability to observe and record ground motion acceleration by deploying new equipment nationwide. Starting in the year 2000, and within a period of four years, a total number of 128 accelerometer stations were installed, Figure 5. Given a national ratio of 0.14 instruments per every 10.000 km2, if the largest seismicity areas are considered, the density is close to 0.5 for every 10.000km2.

The most important records obtained by REDAC originated from the Mw 6.2 earthquake of September 12, 2009. Maximum recorded accelerations reached 0.05g.

The Seismic Engineering and Geophysics departments in FUNVISIS have played a leading role in decision making in choosing new sites to expand the network, although the final place is decided in collaboration with the Electronics Department so as to take into account the connectivity and accessibility of the equipment. The primary criterion is the vicinity to essential civil structures, such as schools, hospitals, fire departments etc., relatively close to a nearby active fault. Subsequently, considerations such as accessibility, connectivity and the possibility of vandalism are taken into account.

Sensor emplacement is almost always done by placing the sensor in a small concrete vault built outside the pertinent facility, a method known as free field installation.

Regarding site characterization, a gross classification in terms of its geological condition is made according to the following classes: hard rock, consolidated soil, and soft soil. Also, in a number of sites, analyses of seismic noise condition, together with other geophysical methods, such as REMI, have been conducted. No particular geotechnical explorations (Standard Penetration Test) have been made so far. Concerning site topography, no particular information is included in our databases other than the fact that all the sites are located in a flat terrain in urban areas.

In most of the stations, in the initial stages, access to the data was achieved via a dial-up connection that now depends on regular maintenance visits to harvest the data. Finally, as regards the type of building construction close to the site that has been instrumented, there is no particular classification other than the use of the given facility by the community.

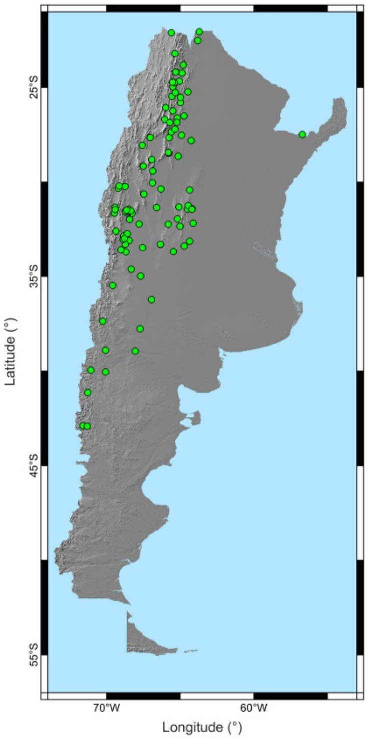


Figure 2. Argentina Network

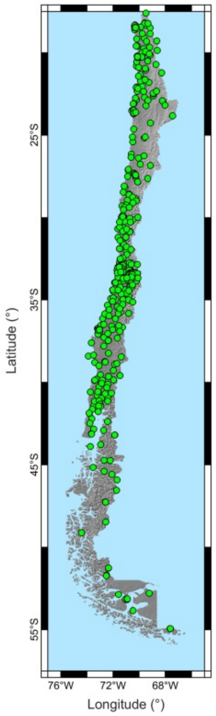


Figure 3. Chile Network

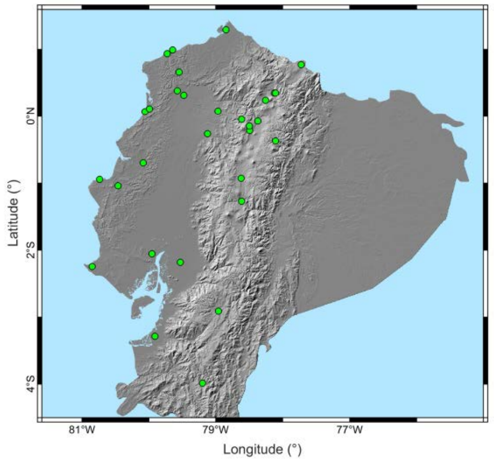


Figure 4. Ecuador Network

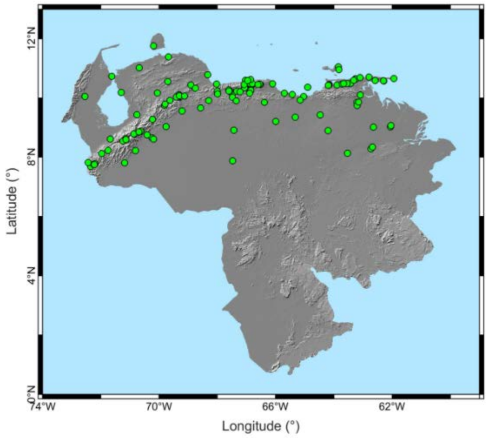


Figure 5. Venezuela Network

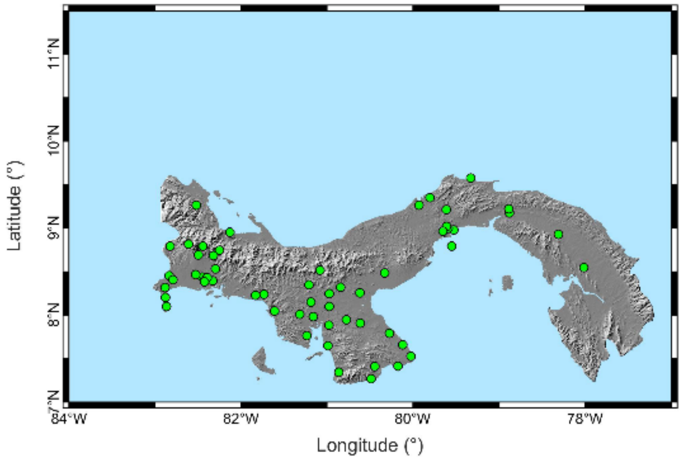


Figure 6. Panama

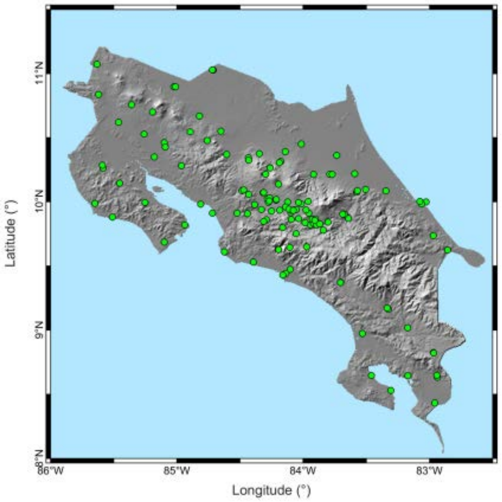


Figure 7. Costa Rica

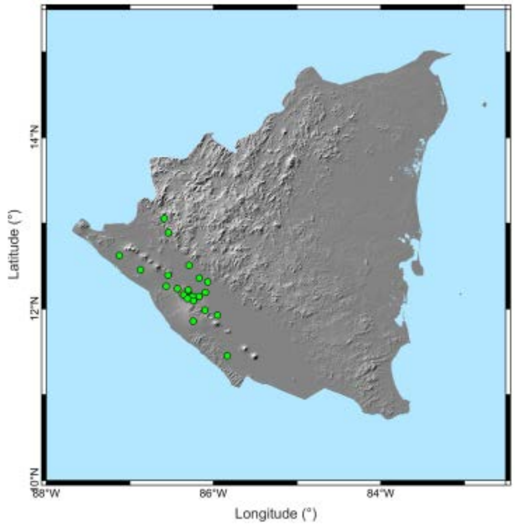
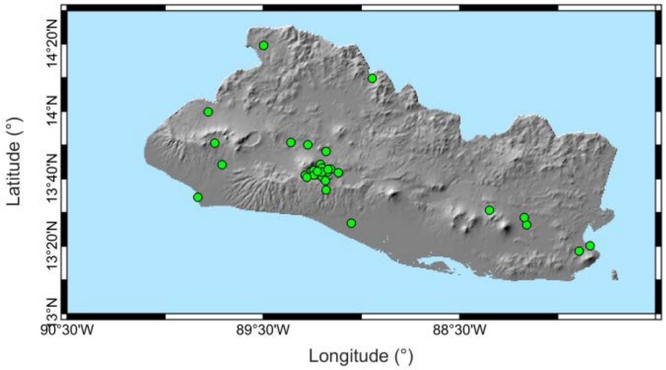
	

Figure 8. Nicaragua	Figure 9. El Salvador Network

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