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GUATEMALAN SEISMOLOGICAL SERVICE: BEYOND DATA ACQUISITION AND SEISMIC MONITORING

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Abstract

The Seismological Service of Guatemala (SSG) is attached to the Engineering, Mathematical and Physical Sciences Research Institute of Mariano Gálvez University of Guatemala and was established in August 2017 through the unification of the Instrumentation and Seismic Record Center (CIRS) – the Strong Ground Motion Unit- with the Seismic Observatory (OS). This is a very important project because on the one hand, it is a modern seismological service in Guatemala, and on the other hand, it took forty one years to carry it out after the great earthquake on February 4 of 1976. This earthquake damaged a lot of buildings and residences in Guatemala City, damaged several major bridges in the road network, destroyed most communities in the rural areas in the country and resulted in more than twenty three thousand (23,000) people left dead.

This paper starts with the seismotectonic framework that gives rise to Guatemala and represents a brief historical review of the seismological service foundation, the network of stations it currently has, the installed high-tech equipment in the main cities of the country, and the seismic monitoring and volcanic activity in the national territory. This presentation also mentions its functions, its objectives, and the products it generates: such as the characterization of soil response where the stations are located (dominant periods), response spectra, shake maps, a catalog of earthquakes and their algorithms of classification that are recorded based on depth, magnitude, geographic area, focal mechanism, dominant period, etc. Other academics and public services are provided, especially to the scientific community, professional engineering associations, the Guatemalan Building Code regulatory body and the Guatemalan population in general.

Keywords: dominant periods, soil response, focal mechanism, strong ground motion, seismic monitoring.

1. Introduction

About 75% of the population of the Republic of Guatemala lives in areas susceptible to seismic hazard. The earthquake of February 4, 1976 that affected a large area of the country with a magnitude of 7.5 Mw, occurred in the area of the Motagua fault (contact area between the tectonic plates of North America and the Caribbean) and its rupture was extended approximately 240 km along the fault; The Uspantán earthquake in the department of Quiché in 1985, originated in the Polochic fault, with a magnitude of 5.0 destroyed more than 500 houses in the town of Uspantán. The Rio Dulce earthquake in the department of Izabal in 1998 of magnitude 6.1 Mw with an epicenter in the Gulf of Honduras, in the Swan Fracture, at the eastern end of the Motagua Fault, damaged important bridges of the road infrastructure; and more recently the San Marcos earthquakes in 2012, 2013 and 2014 that produced numerous victims and large material losses, are just a few recent examples in the seismic history of Guatemala and illustrate the very high seismic hazard of the country.

The earthquake of February 4, 1976, there were horizontal displacements greater than 3 m, causing the destruction of thousands of homes, more than 23,000 dead and 77,000 injured, generating a loss of 10% of the Gross Domestic Product (GDP). The consequences of this great earthquake still have negative effects today, whether in terms of lack of urban planning, concentration of population density in marginal areas or urban settlements, lack of basic public services in these settlements and in a lack of urban planning that seeks give solutions to these collaterals problems. However, in order to successfully implement a public policy aimed at avoiding or reducing the serious consequences that future earthquakes will leave, it is vitally important to have scientific studies that help the authorities to make decisions. And it is precisely with this need that the Seismological Service of Guatemala of the Mariano Gálvez University (SSG) is created to respond to the lack of monitoring of the various seismogenic sources of national territory, have a bank of seismic records and conduct research in Seismology, Seismic and Seismological Engineering to provide technical and scientific tools to government authorities, in the short term and medium term, to facilitate the implementation of urban planning programs, risk management and contingency plans for future and potential earthquakes. In this paper, which is divided into three sections, the seismotectonic context of Guatemala is presented in the first one; in the second part, the mission, vision, objectives of the SSG, networks of equipment that it has today and products that are published and disseminated to the specialized and non-specialized public are exposed; and finally in the third section the most important lines of research are presented at present and in the near future carried out by the SSG.

2. Seismotectonic framework of the Guatemalan territory

The territory of Guatemala is located in the zone of interaction of three tectonic plates: two continental plates (North America and the Caribbean) and one oceanic plate (Coco). The boundary between the North American and the Caribbean plates originates through a system of sub-parallel sinister transforming faults, known as the Chixoy-Polochic-Motagua-Jocotán-Chamelecón fault system. The contact between the plates of the Caribbean with the Coco´s plate is generated outside waters, in the coasts of the Pacific Ocean, where the Coco´s plate submerges under the one of the Caribbean. [1] The transforming fault system interacts westward with the subduction zone, where a triple contact zone is generated.

This triple union of subduction-subduction-transformation, is located off the coast of the Pacific Ocean, the Coco´s plate is added below the North American and Caribbean plates, which are separated from each other by a sinestral running limit, the fault system Polochic - Motagua [1], [2]. In the territory of Guatemala proper, the active limit consists of a sub-parallel fault system, the Polochic and Motagua fault system, which merge eastward.The Polochic - Motagua (PMFS) fault system represents a triple junction arm between the Coco, North America and Caribbean plates. Some authors suggested that the PMFS joins the American Half Trench in the Gulf of Tehuantepec, while others suggested that these boundaries intersect directly west of the PMFS. The latter would not be compatible, since there is no clear intersection between the projected trace of the PMFS and the subduction [3], [4]. The traces of the Motagua and Jocotán-

Chamelecón fault disappear west of the territory of Guatemala below quaternary volcanic deposits. The Polochic fault, on the other hand, extends to the entire continental domain, but does not appear to enter the Pacific Ocean to reach the American Mid-Trench [5]. The location of the triple junction is actually more diffuse; it integrates the northwestern part of Guatemala, southern Mexico and a large part of the Chortí block (Guatemala-El Salvador-Honduras) [6].

The morphogenetics of the territory of Guatemala is controlled by the interaction between the aforementioned plates, generating a large deformation zone. In this area different tectonic environments are distinguished; for example, the Polochic-Motagua fault system, which constitutes the contact between the North American-Caribbean plates and presents a sinestral movement with relative displacement of between 9 and 34 mm per year. To the south of this system, the deformation is of a distensive type, characterized by "gravens" with north-south orientation (N-S), limited by the system of transforming faults in the west-northwest direction and the volcanic arc to the south [7]. The latter is defined to the north by the Jalpatagua fault (of the current dextral type) and is parallel to the trench; at the same time it is divided by local cross-sectional faults typical of said arc. To the north of the Polochi-Motagua fault system, the deformation includes sinister faults with a northwest-southeast direction (NW-SE) and inverse faults [1] [8].In the subduction zone, on the coasts of the Pacific Ocean, the Coco´s plate penetrates below the Caribbean´s plate along the Mesoamerican dorsal, with a convergence speed between 7 to 8 cm per year and an inclination of approximately 45 ° [9]. As a result of this contact, the Central American volcanic arch referred to previously originates. Several of the tectonic characteristics described in the previous paragraphs are observed in Fig. 1.

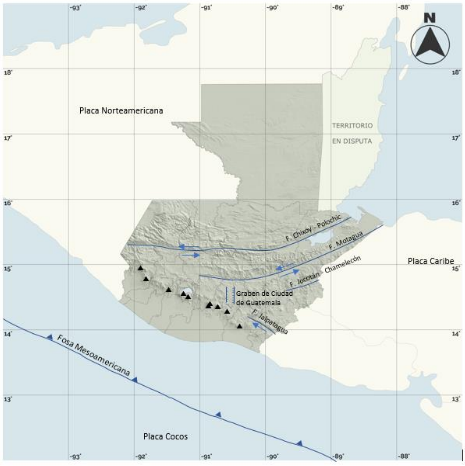


Fig. 1 – Map with the traces of the main structures and morphotectonic elements

3. Macrosismic activity in the Guatemalan territory

The movement resulting from the subduction of the Coco´s plate below the Caribbean´s plate generates significant intraplate earthquakes with magnitudes that can be 8 Mw or 8.3 Mw. The Polochic-Motagua fault system is another seismic source where at least 25 destructive earthquakes have occurred since 1530; including the 7.6 Mw earthquake, which occurred on February 4, 1976, which was previously mentioned. In the volcanic arc, on the other hand, earthquakes of intermediate magnitudes (less than approximately 6.5 Mw) occur, superficial and close to large urban centers [10], so it represents a serious threat to these central populations. The seismicity in the "grabens" is superficial, with historical magnitudes estimated between 5.0 to 7.5 Mw, including a 1976 earthquake replica of 6 ° Mw. In these structures seismic activity usually occurs in the form of seismic swarms [2].

4. Main cities of Guatemala and its seismotectonic context

Among the main metropolises of Guatemala are the cities of: Guatemala, Antigua Guatemala, Escuintla, San Marcos and Xelajú, in the department of Quetzaltenango.

4.1 Guatemala City

Guatemala City is the capital of the country and, according to the 2018 census conducted by the National Statistics Institute (INE), it has a total population of 923,392 inhabitants [1]. This city is located south of the Motagua fault, in a graben-type tectonic valley, which highlights the normal secondary faults such as Pinula, Mixco and El Frutal [2].

4.2 City of Antigua Guatemala

To the southwest of the capital is the city of Antigua Guatemala, a colonial tourist city with a total population of 46,054 inhabitants [1], declared World Heritage by UNESCO. This city is located near the Central American volcanic arch and the possible extension of the Jalpatagua dextral current fault, which runs parallel to it. [3,4].

4.3 Escuintla City

On the south coast of the country is another important economic center, the city of Escuintla. This metropolis has a total population of 156,313 inhabitants [2]. Although it may also be affected by earthquakes in the geological structures mentioned above, the greatest seismic threat in this area is the earthquakes caused by the subduction of the Coco´s plate with the Caribbean´s plate.

4.4 Ciudad de Xelaju (Quetzaltenango) y San Marcos

The interaction of these geotectonic plates also affects other important cities such as San Marcos (47,063 inhabitants) and Quetzaltenango (180,706 inhabitants) [1]. Although there are local faults in these areas, such as the secondary sinister faults of Zunil and Samalá in Quetzaltenango [6]. It is noteworthy that in the city of San Marcos there are significant site effects and amplifications due to topographic effects, as demonstrated by the earthquakes of November 7, 2012, September 7, 2013 and July 7, 2014.

5. Guatemalan Seismological Service

In the month of August of the year 1996, the idea of having a center equipped with instruments for recording and monitoring seismic activity in the country arises, given the deficiencies of existing national institutions. This center, which was initially called the Center for Instrumentation and Seismic Registration (CIRS), would eventually become the Seismological Service of Guatemala of the Mariano Gálvez University (SSG); initiating in this way the efforts to acquire the first instruments necessary for the detection of seismicity in Guatemala, started with the registration of the strong movement. Thus, with this purpose in 1998, the first instrument for the seismic recording was acquired, a first-generation accelerometer, ETNA 1 model. Subsequently and gradually, more accelerometers were acquired and leaving a reasonable time for the the country developed and implemented the infrastructure of a data transfer network, which would later become the INTERNET necessary for the transmission of seismic records from the place where each is located towards the operations center on the university's central campus.

Later in 2011 the first broadband seismometer and an instrument for measuring replicas and site effect, known as Aftershock, were acquired. These teams allow the start of studies of seismic refraction and determination of the dominant soil period in some places of Guatemala City. In 2016, the Seismic Observatory (OS) was created, which is a unit for the location of epi and hypocentres, determining the magnitudes of events that are generated throughout the national territory; as well as the monitoring of telesisms. The Seismological Service of Guatemala was born as such in the month of August 2017, with the unification of the CIRS with the OS and with the installation of a new generation of accelerometers unique in the country, capable of transmitting real-time data from the records of strong movement and the establishment of a network of broadband instruments for the analysis of weak movement and telesisms in order to carry out characterization studies of various seismogenic sources and monitor all seismic activity of the Guatemalan territory. Currently, the SSG has as its main objective the monitoring of the seismic activity that is generated in the Guatemalan territory 24 hours a day, 365 days a year; and its mission is to monitor and record the seismic activity of the Guatemalan territory in order to inform the population and prepare a seismic database that will be used for further studies and research. Its vision is to be a seismological reference service that contributes to the development of the country and to the dissemination of scientific information on seismic activity. The network monitoring interval covers approximately from the State of Chiapas in Mexico, to the northwest, to the country of El Salvador, to the southeast. According to the Gutenberg-Richter relationship, the database is nationally complete, as it contemplates events from 3.58 M, as shown in Fig. 2. Since the accelerographic network currently has a higher density in Guatemala City, it allows Perform studies of microsismisity and microzoning in the capital of the Republic of Guatemala.

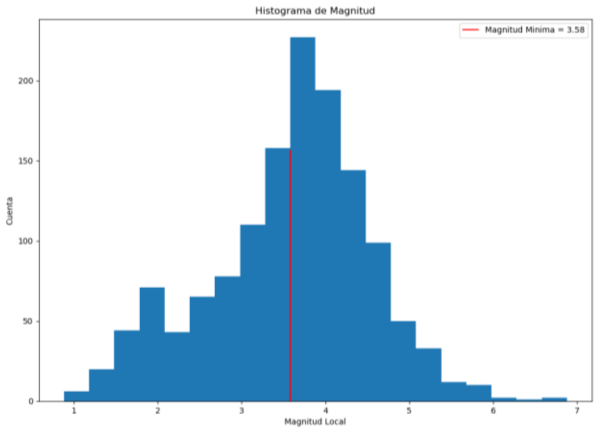


Fig. 2 – Histogram of quantities of events versus local magnitude (source: SSG)

5.1 Strong Ground Motion Network

The network for strong movement monitoring is currently composed of 60 state-of-the-art accelerometers, model ETNA 2, which are installed in the main seismogenic zones and main cities of the country, as shown in Fig. 3; from this account they are able to capture all the seismic movements that occur within the Guatemalan territory, both regionally and metropolitanly. The accelerometers established in the network have interfaces for real-time telemetry and web server, for parameter configuration. In addition, they have the ability to transmit through ORB server, compatible with Antelope acquisition and analysis software or through public domain protocols SEEDLink and Earthworm. The accelerographic network is currently expanding, as it is planned to install a total of 100 accelerometers.

5.2 Roadband Network

The broadband network has a projection of installing around 10 sensors throughout the republic; These instruments are of the latest generation with a response period of 120 seconds, through the terrestrial and satellite internet network. With the objective of making wave velocity measurements to be able to generate intensity maps for Guatemala, these measurements currently do not exist and are of utmost importance due to the issue of site effect, since there is a history with a seismic event that It happened on November 7, 2012 that caused a lot of structural damage in the department of San Marcos.

On June 3, 2018 the eruption of the Volcano of Fire occurs located in the departmental limit of Chimaltenango, Escuintla and Sacatepéquez in Guatemala, the eruption caused the death of more than 300 people and many injured; due to this disaster, the volcanology unit was created. and for the characteristics of instrumentation, software and specialized equipment that is possessed in the seismological service, important information about the volcano was obtained at the time of the eruption; The findings of this were impressive. Using the broadband equipment, the ascent of lava from the magma chamber to the cone structure could be observed at a time interval of approximately 6 hours before the main eruption.

6 Products of Guatemalan Seismological Service

6.1 Seismological Reports

Through these reports, the Guatemalan population is informed about local seismic activity. The information is published in the form of newsletters, which have a periodic dissemination, whether weekly, monthly and yearly. A special newsletter is also published when a significant event occurs. A sample of these reports can be seen in Fig. 3.

6.2 Website ande Online Catalog

The website contains all the information of the SSG and it is through it that the seismicity analyzed is made known. It also contains a catalog with earthquakes for consultation and an information resources section. A sample of the web page screen described above is shown in Fig. 3.

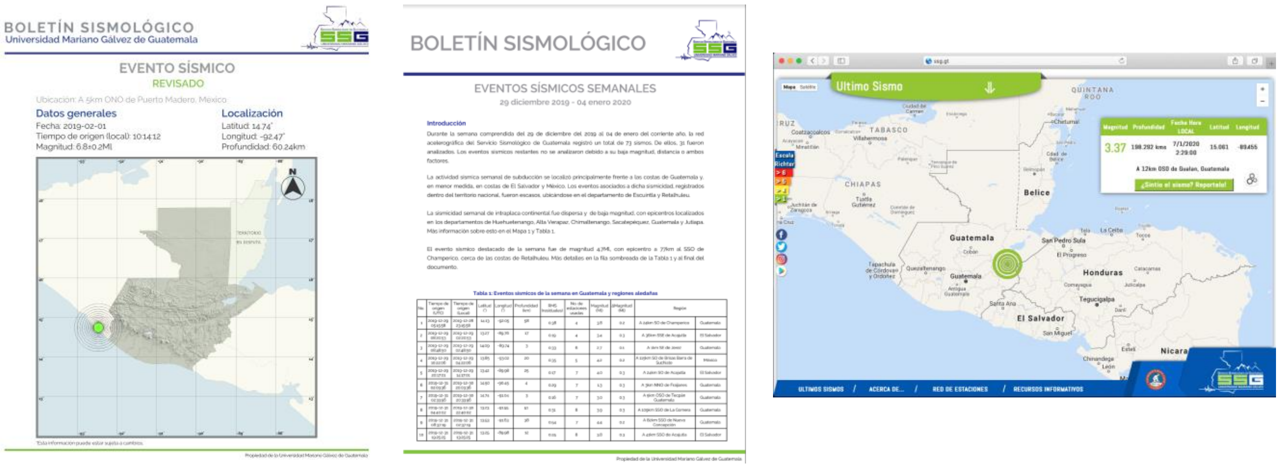


Fig.3 – Seismological bulletins for periodic publication and seismic activity (left) and web page of Guatemalan Seismological Service (right) (source: SSG)

6.3 Animation for epicenter location

In the center of operations of the SSG animations are elaborated that illustrate the location of the epicenters of the monthly seismicity, according to the magnitude and depth. All this in order to disseminate seismological information in a more dynamic and visual way. These animations allow you to analyze patterns that otherwise could not be or would be more difficult to observe in a conventional image.

6.4 Infographics and informatics capsules

Infographics are used as educational tools that are disseminated in social networks; Through this educational material it has been possible to demystify the erroneous information that the public has about seismology and earthquakes.

6.5 Shakes maps

Intensity maps are the tool that provides the best information regarding the severity of an earthquake in a given geographical area. The instrumental intensity calculation of each station is carried out based on the value of the Peak Ground Acceleration (PGA), filtering the signal of all noise. This was achieved through a Butterworth bandpass filter that eliminates the baseline deviation, probably caused by other natural phenomena that have low frequencies, and high frequency noise, whose possible origin is interference from other electrical appliances.

For the calculation of the PGA the largest value of the absolute value of the values of each the signals for its two horizontal channels is located. Then, the PGA value thus reported for the station is found by obtaining the geometric mean at the horizontal values obtained [11]. The model proposed by [12] is used to calculate the intensity:

$$\text{INT} = \alpha_1 + \beta_1 \text{logPGM}, \text{ si logPGM} \leq t_{PGM} \quad (1)$$

$$\text{INT} = \alpha_1 + \beta_1 \text{logPGM}, \text{ si logPGM} > t_{PGM} \quad (2)$$

Where INT is the intensity; a, b are constants of the model according to Table 1 and PGM is the maximum value of the movement. For the preparation of the maps, the PGA was selected as the measurement value, so t = 4.87 [12].

Table 1 – Model values used for the conversion of PGA to Mercalli instrumental intensity

Region	t_{PGM} ($\log_{10}$PGM)	α_1	β_1	σ_{x_1}	σ_{y_1}	α_2	β_2	σ_{x_2}	σ_{y_2}	t_{INT}
Global	PGV 0.3 ± 0.2	4.424	1.589	0.6	0.9	4.018	2.671	0.5	1.3	4.92 ± 0.3
	PGA 1.6 ± 0.2	2.270	1.647	0.4	0.7	−1.361	3.822	0.4	1.4	4.87 ± 0.3

PGM, peak ground motion; PGV, peak ground velocity, expressed in centimeters per second; and PGA, peak ground acceleration in centimeters per second squared; σ, errors on x and y axes for the global relations.

After calculating the intensity for each station of the accelerographic network, we proceed to perform a linear regression between the intensity values and the hypocentral distance as shown in Fig. 4. Finally, the results are presented by plotting the intensities of each locality where the accelerometric stations and the intensities map are found by means of the attenuation relationships as can be seen in Fig. 4.

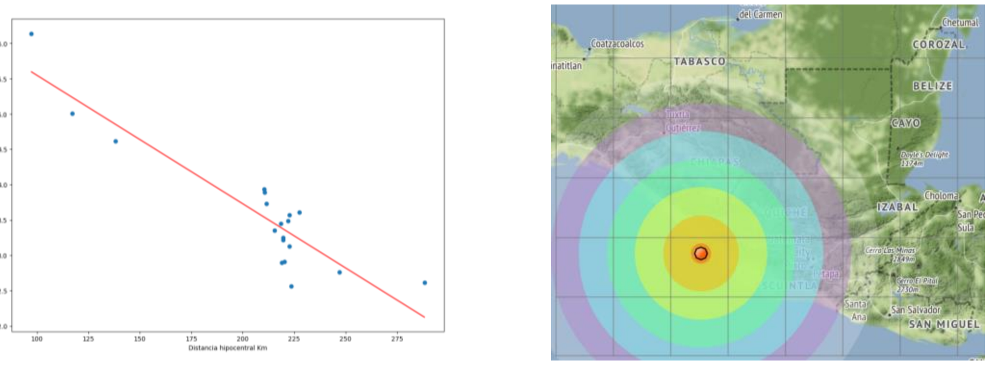


Fig. 4 – Linear Intensity Regression versus epicentral distance (left) and Maps of intensity isosists by stations, these correspond to the epicenter of the simo of March 1, 2019, located in Puerto Madero, Mexico (right) (source: SSG)

7 Investigation of Guatemalan Seismological Service

7.1 Evaluation of Seismological Phenomena

Through the signals recorded by the accelerographic network it has been possible to study several seismological phenomena. Among these phenomena are the earthquakes of Puerto Madero, Mexico in 2019; La Libertad, El Salvador, 2019 and La Gomera, Guatemala, 2019. All these events have a local magnitude equal to or greater than 5.5 MI. Another interesting case study is the signals recorded in 2018 and that are probably associated with one of the most active volcano eruptions in Guatemala: the Fuego volcano. Several seismic swarms have been monitored as illustrated in Fig. 5, they have been monitored and analyzed in the vicinity of Guatemala City, through the metropolitan accelerographic network.

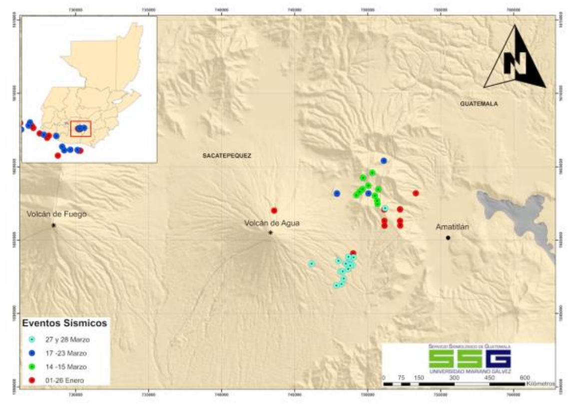


Fig. 5 – Epicentral location map of seismic swarms that occurred in the canyons to Guatemala City in the 2019. (source: SSG)

7.2 Subduction study between the Coco and Caribbean Plates

With the seismic records analyzed to date, a comprehensive seismological catalog of the region has been built. Using this catalog, you can perform various studies and research. Among these studies, the analysis of the inclination with which the Coco´s plate is submerged below the Caribbean´s plate stands out. In Fig. 6 you can see the inclination and the slope of the same, obtained with the analysis of a year of records.

7.3 Recurrence Evaluation and Seismicity Classification

Another aspect that is evaluated through a catalog of earthquakes in the region is the number of events expected with a certain magnitude a certain period. The methodology used for this purpose is the Gutenberg-Richter relationship. Using a year of records, some initial trend can be seen, such as that shown in Fig. 6, which will be recalibrated in the following years when there are a greater number of records.

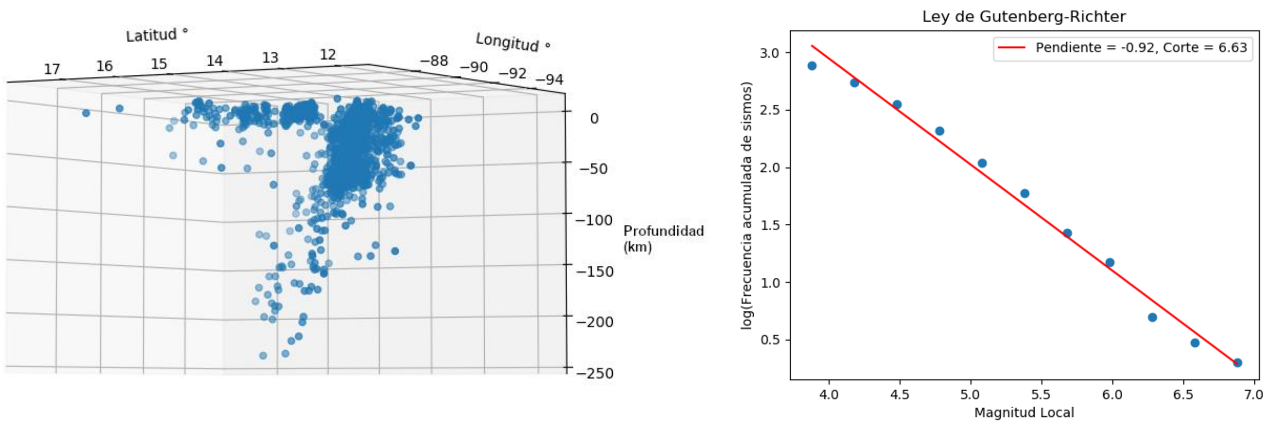


Fig. 6 – Seismicity distribution according to location and depth (left) and graphical representation of the Gutenberg-Richter relationship with one year of analyzed data (right) (source: SSG)

Analyzing the same records, seismotectonic characteristics of the region can be evaluated. For example, and according to the location of the seismic events and the depth of them, it can be identified that the majority of events correspond to interplate and intraplate seismicity of superficial and intermediate depth for the profile of a study area of the territory of Guatemala, as shown in Fig. 7.

Seismicity assessments of latitude can also be performed versus months of the year; such is the case shown in Fig. 7. In it can be seen that the recurrent seismicity was greater for the month of March, because said recurrence is associated with the generation of a seismic swarm recorded in said month.

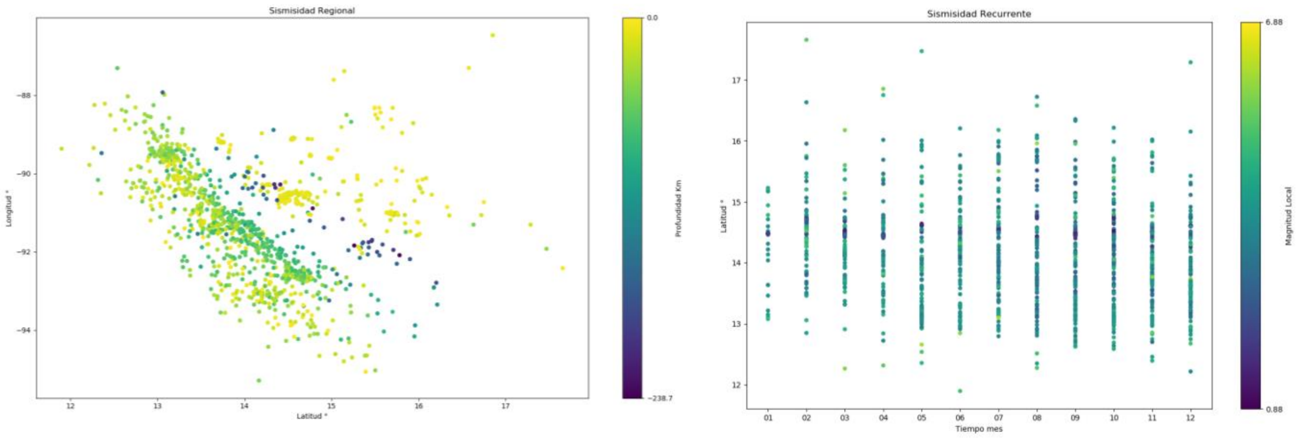


Fig. 7 – Distribution graph of the local seismicity according to location (left) and Graph of spatial and temporal distribution of earthquakes according to magnitude (right) (source: SSG)

7.4 Determination of Amplifications in the Guatemala City

Through the records obtained by the strong ground motion network in Guatemala City, after processing and analysis with random vibration theory, the behavior of the soil in the city valley has been determined. These site effects correspond to amplifications of soil movement that occur in a range of values of approximately 2 to 5. This study will be complemented in the future as the number of records available in the SSG database increases. In Fig. 8 three examples are presented for different periods and several seismic scenarios that cause earthquakes in the Guatemala City valley.

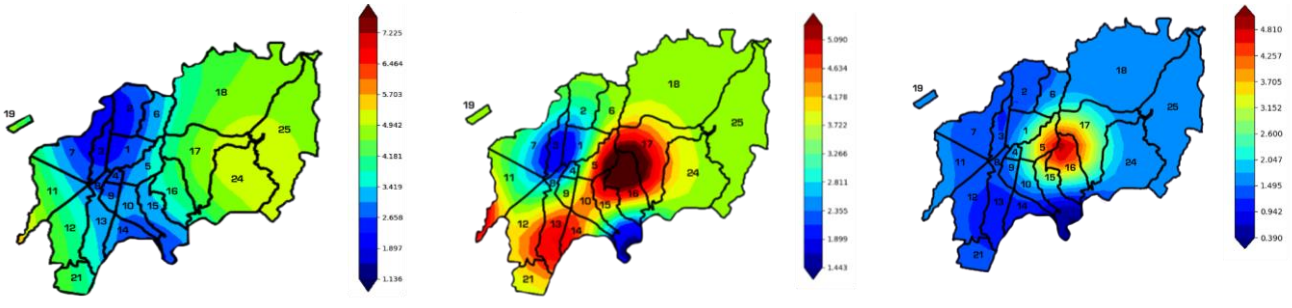


Fig. 8 – Seismic acceleration maps of Guatemala City, for PGA, T=1s and T=2s.

7.5 Seismic Alarm and Early Warning

The seismic alarm is a device that has been developed during the last 3 years to be implemented as a seismic alarm; this alarm is derived as a response to the problem of not having a seismic alarm in Guatemala, which can be acquired and implemented as part of prevention systems in buildings, hospitals and universities. Some buildings and companies have institutional protocols in this area, but there is a lack of a device that can alert them to their presence. The seismic alarm is activated when a movement occurs that exceeds the ranges of perceivable quantities, it records the earthquake and activates a sound and light warning in emergency signal. This alarm announces that you must proceed to protect yourself in safe areas and look for evacuation exits. This seismic alarm is being designed to issue the stored records to an information portal managed within the facilities of the SSG. The data collected from multiple accelerometers that make up the seismic alarm network will be used to analyze inefficiencies in the different areas and regions of Guatemala. This alarm is also being designed so that in the coming years it will function as an early warning system, which will be a great contribution to disaster reduction in Guatemala.

7.6 Mercalli Application

Creation of an application for Android systems that generates intensity maps based on Mercalli scale. This application is designed for mobile devices, which at the time of a relevant event people can contribute and rate the intensity level based on the modified Mercalli scale. With this data you can generate in real time a map of intensity with the contribution of users of mobile systems, that is, this application can provide a lot of information in a few minutes. The result of this application is a map of intensities when a relevant event occurs, you can provide thousands of data in a matter of seconds, or depending on the population has sent your information.

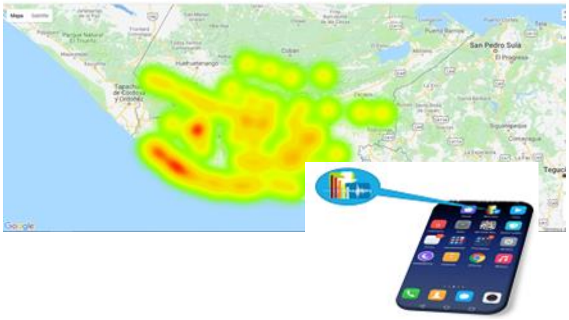


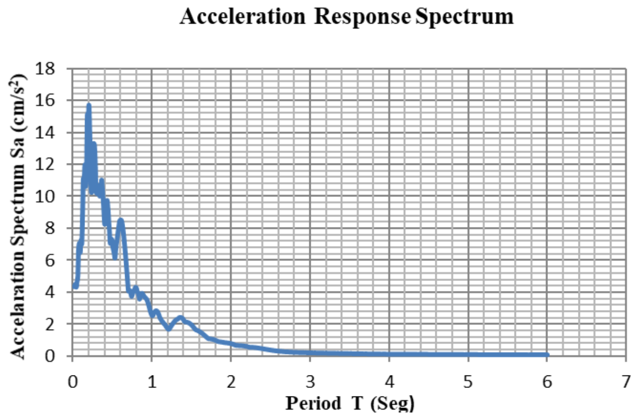
Fig. 9 – Mercalli Application development by SSG in a phone cell

7.7 Safe Buildings

A continuous and permanent line of joint research with the Engineering, Mathematical and Physical Sciences Research Institute of the Mariano Gálvez University is the design of electronic devices dedicated to deactivating facilities (gas, electrical) and vertical circulation systems (elevators) previous moments of the arrival of the secondary waves of a significant earthquake. These types of devices are extremely important, since thousands of people have been victims in buildings where the fire has occurred due to the rupture of the gas pipes and electrical cables of the power supply that have been destroyed during an important earthquake. For this type of electronic devices to be implemented successfully, that is, so that the control system, on the one hand, can immediately connect and / or disconnect gas and electricity supplies, and on the other, so that the elevators are controlled in such a way that they are stationed at evacuation sites and subsequently blocked for their use, it is necessary to have a bank of seismic records, with which an efficient algorithm of differentiation between the arrival of the primary waves can be designed and the secondary waves of an earthquake; Therefore, the SSG provides an incomparable and fundamental support for the design of said algorithm and the subsequent electronic design of these control devices.

7.8 Contribution to the update of Guatemala Building Code

In order for the response spectra to be useful for the elaboration of design spectra and their subsequent publication and use in the Guatemalan Building Code, as shown in Fig. 15, it is necessary that the seismic records from which these response spectra obtain representative and characteristic records of the various seismogenic sources in the country. It is there where the accelerometric network of the SSG has an imponderable role in providing good quality records for the elaboration of response spectra and in the calibration and / or verification of the design spectra that will be used by structural engineers Likewise, in conducting seismic microzonation studies that identify areas with potential significant site effects that must be taken into consideration for the determination of the seismic load.



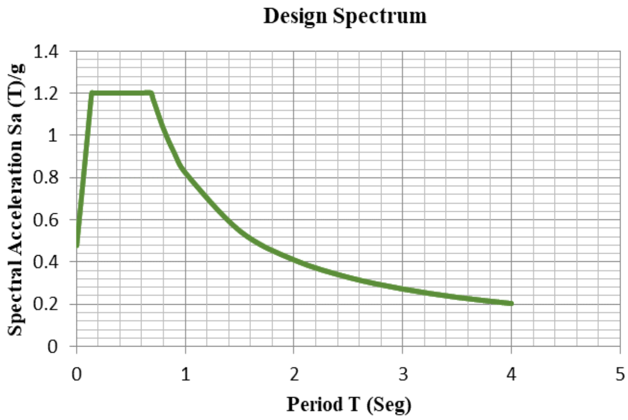


Fig. 10 – Acceleration response spectrum graph (left) and design spectrum graph (right)

8 Conclusions

Guatemala is a country with a very high seismic hazard, because its territory is made up of three geotectonic plates that of North America, the Caribbean and Coco.

Depth studies of focus or epicenters carried out to date contribute to a better definition of the contact area in subduction zone.

The amplification studies show that there are significant site effects in the Guatemala City.

The records of earthquakes registered through the strong motion network form a database that will be used to prepare and / or complement the future design spectra of the Guatemalan Building Code.

The Guatemalan Seismological Service (SSG) provides a highly beneficial service for the country, whether it is to disseminate important information regarding earthquake warnings to the Guatemalan population, monitoring of seismogenic regions and scientific studies of seismology, seismic and seismological engineering; as well as providing records for use in implementation programs of early warning and safe buildings.

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