A Large Earthquake in Quito (Ecuador) : Ground Motion Simulations and Site Effects

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SUMMARY:
We have simulated realistic accelerograms generated by large earthquakes in the city of Quito, Ecuador, using the recordings of two small earthquakes (Mw 3.9 and 5.2) as empirical Green's Functions.
Two scenarios have been considered, in accordance with historical seismicity: a Mw 7.1 event that would occur on a fault in the Sierra, 100 km south east of Quito, and Mw 6 and 6.4 events that would occur on a fault close to the city. We have found that this last scenario is able to generate very large accelerations inside Quito (PGA = 0.7 g at one station). In parallel, we have determined H/V ratios from earthquakes and ambient vibrations using data collected on seismometers co-located with the accelerometer stations and found low frequency amplification in the southern part of the city (0.35 Hz), which may indicate that the basin is relatively deep under Quito.

Keywords: Ground motions, simulation, stress drop, site effects, seismic hazard, Ecuador

1. INTRODUCTION

The city of Quito (Ecuador) is situated in a valley prone to seismic hazard. 241 earthquakes of magnitude larger than 5 have been recorded since 1988 by the national seismic network (Figure 1).

Many historical earthquakes have been reported such as the events of 1587, 1755, 1797, 1868 and 1949 that have produced intensities equal or larger than VII (Del Pino et al. 1990).
The last important earthquake that has strongly affected the city occurred in 1868 (Ibarra, maximum intensity IX, Mw 7.1, from Beauval et al, 2010). With the population increase to 2.5 millions, with much of its dwelling in poorly constructed houses and unstable sites, damage from future earthquakes in Quito could be devastating.

Quito can be strongly affected by three kind of earthquakes: (1) events with magnitude larger than 8 coming from the subduction zone located at more than 200 km (e.g. Esmeralda, 1906, Mw 8.8), (2) shallow events with a magnitude 7 to 7.5 from the Andes cordillera and originated about 80 km away or more and (3) events with a magnitude 6 to 7 occurring on faults close to the city.

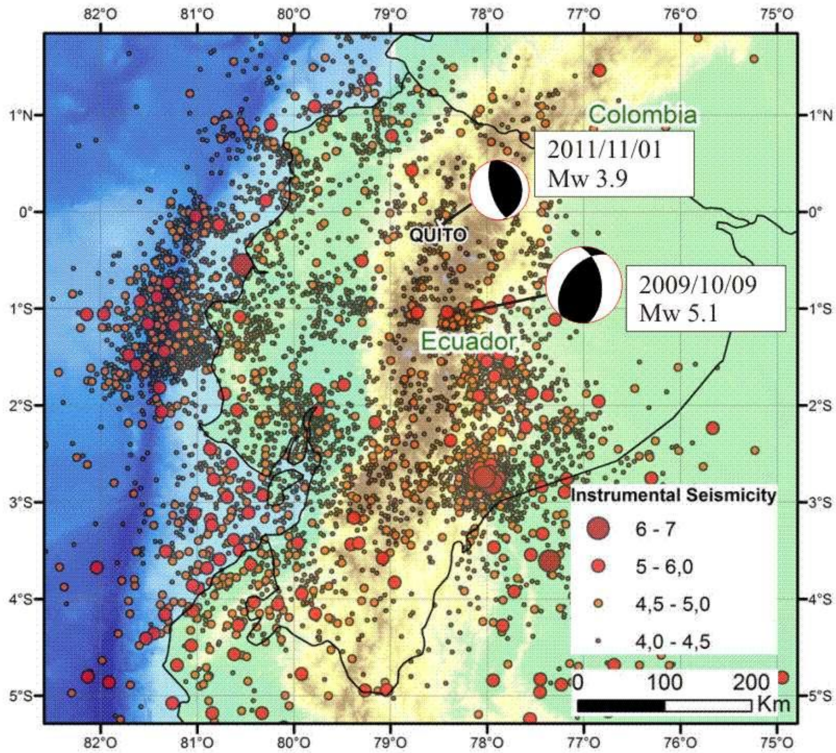

Figure 1 : Instrumental seismicity (M>4) in Ecuador since 1988 recorded by the national seismic network (red dots). Focal mechanisms of the two events used as empirical Green's functions in this study.

There are several faults around Quito that could generate damaging earthquakes. Among them, 'Quito Fault' is considered as the most important for seismic hazard purposes. It has a maximum probable earthquake magnitude estimated between of 6.9 to 7.1 Ms with a return period between 1500 and 4000 years and with a focus under the city (Soulas et al., 1991).

The valley of Quito is also known to generate site effects. The frequency dependence of soil response was studied by Guéguen et al. (2000), founding two amplification frequencies in several sites. The results were compared with the surface geological map of the Ecuador, Earthquake Risk Management Project (Escuela Politecnica Nacional et al. 1994).

For monitoring the city, an accelerometer network has been installed since 2009. The network consists of 17 accelerometers (Guralp CMG-5TD) that record in continuous mode the ground acceleration with a sampling frequency of 100 Hz. The collected new data enable to obtain first estimations of the ground motions in the city of Quito. We took advantage of the largest events (magnitude 3.8 to 5.6) that have been well recorded by the network to simulate the accelerograms that could be generated by larger earthquakes in the same zones and also to determine site effects using H/V spectral ratios.

In this paper, we will focus on the simulation of two large events: an earthquake that would occur in the Andes cordillera using a Mw 5.1 event as empirical Green's function, and an earthquake that would occur on a fault near Quito using à Mw 3.9 event that has been very well felt in the city.
In parallel of the accelerometer network, temporary seismometers have been deployed at the same sites, and recorded ambient noise during half an hour to quantify site effects. The first results obtained using earthquakes and ambient vibrations are also presented.

2. GROUND MOTION SIMULATIONS METHOD

The usual way to predict ground motion in a given region and for a given earthquake is to use empirical relationships also called Ground Motion prediction Equations (GMPEs). The use of GMPEs is for example crucial for probabilistic seismic hazard assessment. No specific GMPEs exist for Ecuador yet and the selection of suitable GMPE's based on data from other countries is still an ongoing work. Anyway, predicting the ground motion using GMPE's does not enable a good reproduction of local site effects and do not provide synthetic accelerograms.

In order to obtain realistic accelerograms in a broad frequency range that takes into account path and site effects, we used an empirical Green's function (EGF) approach (Hartzell 1978). A small, well recorded event is chosen in the region of interest. Its recordings, called Empirical Green's Functions (EGFs), are combined in order to produce realistic accelerograms corresponding to a larger earthquake with the same focal mechanism. We assume that the recordings of the small event represent the Green's functions at each point of the fault plane activated during the rupture of the large simulated event. This approach takes directly into account path and site effects at different stations, as they are included in the EGFs.

Among the possible EGF's methods, we used a stochastic, two-step method proposed by Kohrs-Sansorny et al. (2005). The main advantage of this method is that it correctly provides the ω-2 model spectra not only at low and high frequencies, but also in the transition region (between the corner frequencies of the small and large events). Moreover, it requires only few input parameters, which is a great advantage for simulating an unknown event. This method has proved its efficiency for simulating the ground motions of moderate size earthquakes, provided that a proper small event could be chosen as EGF (Courboulex et al., 2010). It has also been recently used to simulate damaging earthquakes in the south of France (Salichon et al., 2010; Honoré et al., 2011).

The only input parameters that have to be specified in the simulations are: (1) The seismic moment (m0) and the corner frequency (fc) of the small event taken as EGF, which are directly determined from the data (see paragraph 3.1); (2) The seismic moment (M0) of the target event (see paragraph 3.2); (3) The ratio C between the static stress-drop of the target event and that of the small event. The simulation process produces a large number of accelerograms, representing diverse random rupture processes on the fault, for the same focal mechanism and moment magnitude.

3. SMALL EVENT USED AS EGF AND LARGE EVENTS SIMULATED

3.1 Characteristics of the Events selected as empirical Green's functions

The new accelerometer network in Quito has recorded now several small events. We used in this study the recordings of two earthquakes particularly well recorded, and which location is interesting for seismic risk assessment:

- The first one occurred near the city of Tena, 100 km to the south East of Quito. In this zone, many active faults have been recognized and several historical earthquakes have been reported (Figure 16 in Beauval et al., 2010).

- The second one occurred very close to Quito on a fault not yet well identified but that is related to the system of faults of Quito (Alvarado, personal communication).

Both events have been recorded with a good signal to noise ratio at more than 10 stations in the city of Quito (see examples of recordings on Figure 2).

3.1.1. Moment and focal mechanism determination

We made an inversion of the seismic source to retrieve the focal mechanism and the seismic moment of both events using the waveform fitting method described in Vallée (2012). Data from 12 stations of accelerometers and broad band sensors of the national network of the Instituto Geofísico de la Escuela

Politécnica Nacional of Ecuador have been used. Several inversions were performed, changing the filtering window.

For the event in Tena, the focal mechanism that fits better, was mainly inverse, this agrees with geodynamics of the faults and coincides with the Global CMT result. The best value for Mw is 5.1. For the event close to Quito we have found also a reverse focal mechanism with Mw value equal to 3.9. Both focal mechanisms are represented on Figure 1.

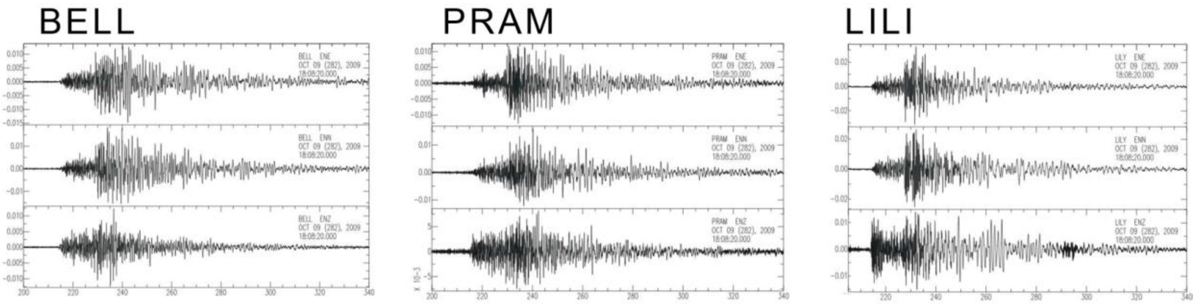

Figure 2 : Example of 3-components recordings of the Tena earthquake (Mw 5.1) on 3 stations of the accelerometric network in Quito

3.1.2. Corner frequency determination

The corner frequencies of the 2009 and 2011 earthquakes are determined from displacement spectra assuming an ω-2 source model (Brune 1970). The low- and high-frequency sides of the Fourier amplitude spectra are fit with the ω0 and ω-2 asymptotes, respectively, and the corner frequency is given by their intersection. When no large difference is found between the stations, the average value of fc is kept. The characteristics of both events are presented in Table 1.

3.2 Characteristics of the large target events

Two parameters have to be determined for the large target events: magnitude and stress drop ratio between the large and the small event.

For the event in the south (Tena event) we propose to simulate a Mw = 7.1 event, equivalent to the value determined by Beauval et al (2010) for the 1698 Ambato earthquake.

For the event near Quito we took two values: a magnitude 6 earthquake that is highly probable in this zone and a magnitude 6.4 one that is the value estimated for the 1587 Guayllabamba earthquake (Beauval et al, 2010).

Determination of the stress drop ratio parameter C is difficult as we have no a priori constraints on the stress drop of the large earthquakes. It is thus important to take into account an uncertainty on this parameter. We run different simulations for which the stress drop ratio parameter C is set at different values. For the Tena event we have kept values of C that corresponds to rupture durations between 9s and 30s. For the earthquake near Quito we have kept a value of C=1 and two different values of magnitude because the variability of close by event needs further analysis to be chosen correctly. Parameters for the EGF and the target events are summarized in Table 1.

Table 1. Characteristics of the earthquakes used as EGF and the large simulated earthquakes

Small events selected as EGF									Large events to be simulated	
Date	*Lat*	*Long*	*Depth*	*Strike*	*Dip*	*Slip*	*Mw*	*Fc (Hz)*	*Mw*	*C*
2009/10/09	-0.995	-77.962	17	359	48	66	5.1	0.45	7.1	0.9<C<6.4
2011/11/29	-0.132	-78.369	12	358	24	103	3.9	1.74	6/6.4	1

4. SIMULATION RESULTS

For each scenario and each values of C, we have generated 500 simulations on each station and each component. A simulation corresponds to a given source process. We first present the simulations for a Mw 7.1 event 100 km away. The values obtained are compared with the estimations of GMPE's. Then we present the results of the simulation of smaller earthquakes (Mw 6 and 6.4) that would occur on a fault close to Quito.

4.1 Scenario 1 : a Mag 7.1 earthquake 100km away from Quito

For each of the simulated accelerograms we found elastic response spectrum, which describes the maximum response of a one-dimensional damped oscillator, affected by a movement of the ground as function of its natural frequency (Figure 3). The values at each station are quite low, with a maximum average value for PGA always lower than 0.1 g.

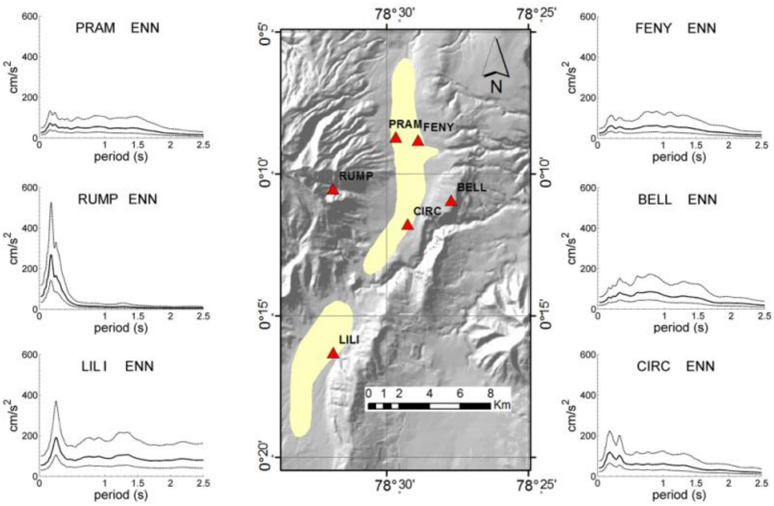

Figure 3 : Simulation of a Mw=7.1 earthquake coming from the region of Tena, 100km to the south of Quito. Elastic response spectra are represented for North-South component of each station. The black curves show the average and percentiles 16 and 84 of 4500 simulations that correspond to 9 different values of C. The yellow area in the map of Quito is the center of the valley formed by lacustrian deposits.

The shape of the spectra can be divided in three groups: (1) the stations in the north (FENY, PRAM CIRC and BELL) show almost flat response spectra between period of 0.2 seconds to 1.5 sec, with a zone of higher values around a period of 0.25 sec. The similar shape of spectra can be easily understandable for stations PRAM and FENY, which are very close to each other and on the same geological context. The similarity with station BELL, which is outside the valley, has to be explained. (2) Station RUMP that is located in a ravine outside the valley, shows very strong amplitudes at periods lower than 0.5 sec and very low values for larger periods. This station has the strongest PGA obtained for this scenario. (3) Station LILI in the south of the city shows the same peak than RUMP at low periods but it presents also large values at larger periods. This result will be compared latter with the H/V measurements realized around the stations.

4.2 Comparison with ground motion prediction equations

As mentioned before, there are not yet any GMPE that have been built or selected for Ecuador. We have compared our results with the models of Ambraseys et al. (2005) and Chiou and Youngs (2006), built from data of active regions with shallow crustal seismicity. These two models yield identical results, so we only show here the comparisons with that of Ambraseys et al. (2005).

We show the comparisons on three stations that corresponds to the three groups of stations defined before, located in different parts of the basin of Quito (Figure 4):

- Station CIRC (group 1, north of Quito). The shape and values predicted by GMPE's and by the simulations are rather similar for all periods.

- Station RUMP (group 2, outside of the valley). The PGA and response spectra at periods lower than 0.5 sec is much higher in our simulation than predicted by the GMPE. For higher period, at the contrary, our simulations are much lower.

-Station LILI (group 3, south of Quito). The shape of the spectra is rather similar for low periods but the simulations are much larger for periods larger than 0.5 sec.

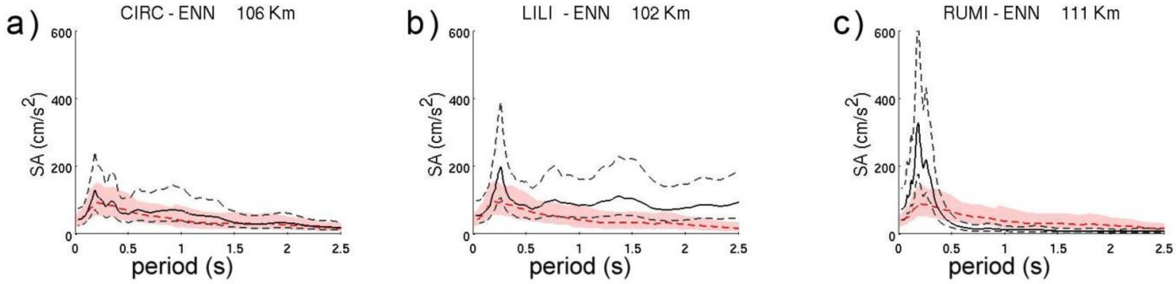

Figure 4 : Elastic response spectra for scenario 1 (Mw 7.1 event at more than 100 km). Simulation results are represented by continuous black lines (dashed lines shows median value +/- sigma) and GMPEs predictions using Ambraseys et al. (2005) by red lines (pink zones for values +/- 1sigma). (a) Station CIRC at the north of Quito (b) Station LILI at the south of Quito, c) station RUMP at the north oust, outside of the valley.

4.3 Scenario 2 : magnitude 6 and 6.4 earthquakes near Quito

The simulation results obtained for Mw=6 and Mw =6.4 are presented on Figure 5 and Figure 6 respectively. The results are presented on the same stations than for scenario 1. For these simulations we haven't taken into account the stress drop variability of the large event, because we need further investigation to fix it. We have supposed that the stress drop of the large events was the same than the one of the small one. In other terms, the value of C is set to 1 and the sigma values are computed on only 500 simulations, that's why they are smaller than for scenario 1. Because the earthquake occurred close to the city (the epicentral distance is 12km for FENY and 24km for LILI), the simulations at each stations cannot be compared, as it was possible for the scenario 1.

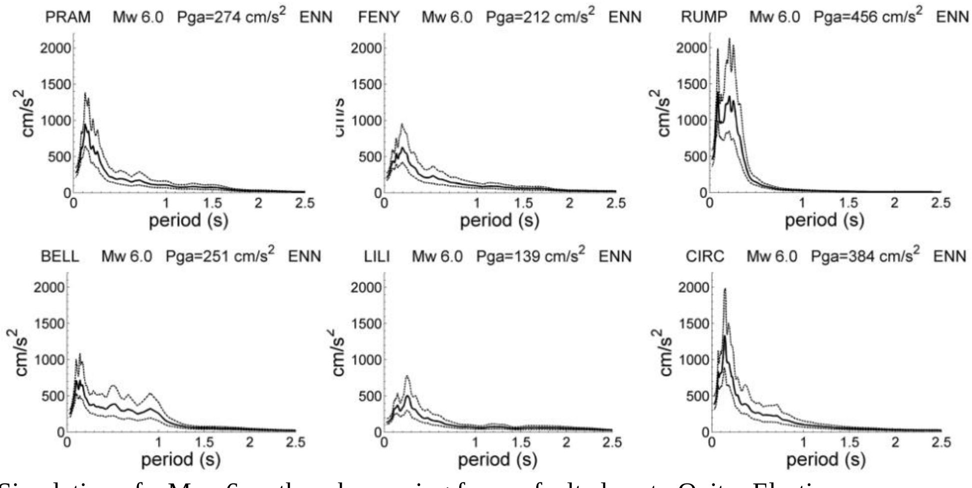

Figure 5 : Simulation of a Mw=6 earthquake coming from a fault close to Quito. Elastic response spectra are represented for North-South component of each station. The black curves show the average and percentiles 16 and 84 of 500 simulations that correspond to a value of C=1.

For the Mw=6 event, we have found values of PGA from 0.14 to 0.45 g. Because the earthquake occurred to the north, we would except stations situated is the north of the valley (see figure 3 for the station locations) that have the highest values. This is generally the case because the simulated ground motions for station LILI situated in the south is much lower. Nevertheless, RUMP and CIRC, which are not the closest stations, have the highest PGA values.

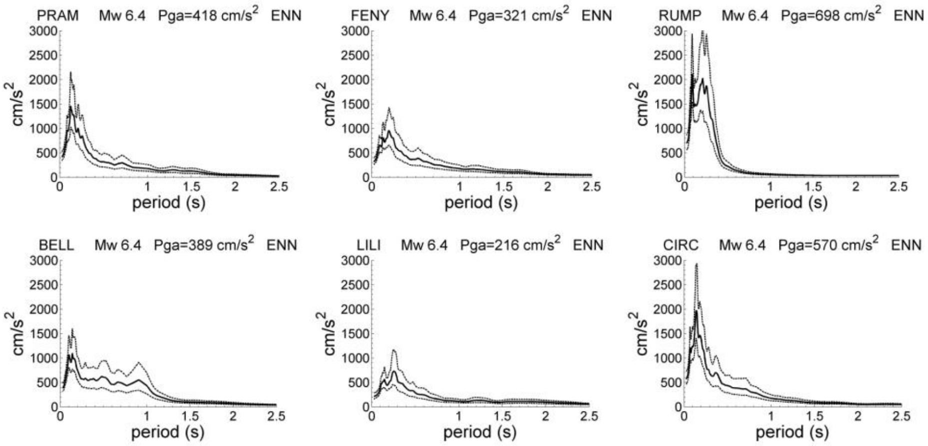

Figure 6 : Same a Fig 5 for a Mw=6.4 event

For the Mw 6.4 event, the values are much larger and reach 0.7 g at station RUMP. This value shows that such an event is able to generate important destructions in the city of Quito.

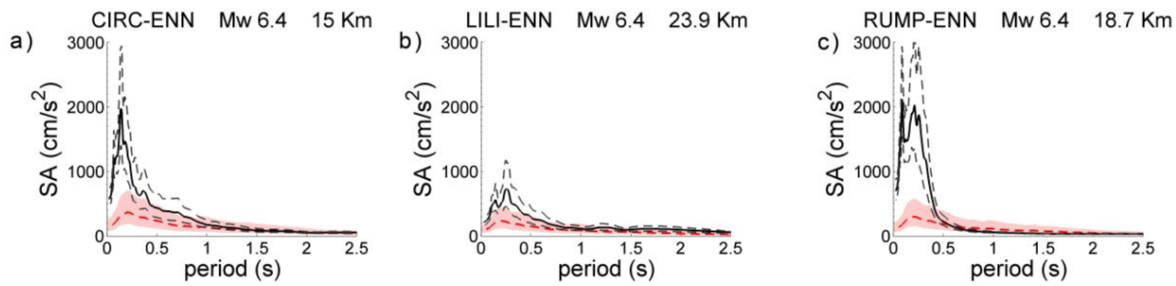

Figure 7 : Same than Figure 4 for a Mw 6.4 earthquake near Quito

If we compare the results obtained with the predictions of Ambraseys et al. (2005) GMPEs, we obtain that the simulation values are much higher on each station, and especially on stations RUMP and CIRC, that seems to be prone to high frequency amplifications (Figure 7). Note that the small earthquake (Mw 3.8) was very well felt in Quito and had PGA values larger than expected for such an event.

5. H/V MEASUREMENTS IN QUITO

We use two techniques to find the amplification frequencies in 16 of the accelerometer network stations, installed in Quito.

5.1. Spectral ratio method H/V on ambient vibrations

The method of Nakamura (1989), ratio of the horizontal components of the noise spectrum with respect to the vertical (H/V), has been used to obtain the fundamental frequency of resonance of the soil column. We followed the SESAME (2004) project specifications to perform the field measurements. Because accelerometers are not sensitive enough for record noise at frequencies lower than 1 Hz as it is stated in the guide of SESAME (2004), we measured the noise with a seismometer LE-3D/5s in each of the sites where accelerometer stations are installed. The recording time varies between 20 minutes to an hour. The software GEOPSY was used to process the data (www.geopsy.org).

5.2. Spectral ratio method H/V for earthquakes (Receiver Functions)

We use the records of the accelerometer network in Quito, to compare the results of measurements of ambient noise with the method of the Receiver Functions (RF) (Lermo and Chavez-Garcia, 1993). The RF method computed the spectral ratio between the horizontal and vertical components of earthquakes data. Bonilla et al. (1997) and Parolai et al. (2004) found that this technique reproduces the shape of the response of the site, but does not indicate the amplification factors. We have chosen events having a good signal-to-noise ratio. From 6 to 12 earthquakes were selected for the implementation of RF at each station.

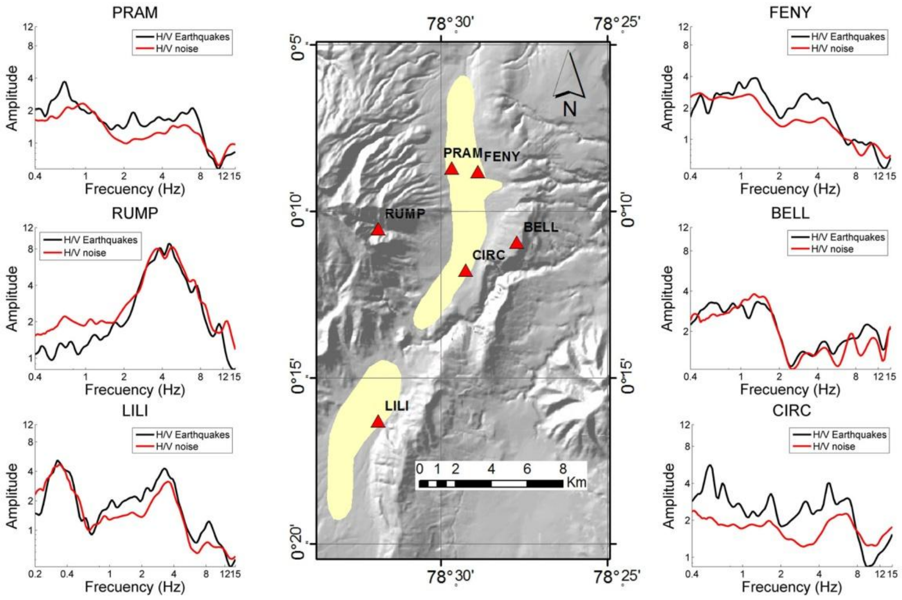

Figure 8*:* Spectral ratio H/V in the city of Quito from Ambient Noise (red line) and on earthquakes (black line). The area in yellow on the map represents the central depression, recent lacustrine deposits covered with a layer of soft soil (Escuela Politécnica Nacional et al., 1994). Red triangles are the stations. Results are shown only for the stations were ground motion simulations have been realized.

We superpose the result of the spectral ratio of ambient noise H/V and the mean of the ratio H/V for earthquakes for only the 6 stations in Quito were ground motion simulations have been realized. We found a very good agreement of the results using both methods (Figure 8). Stations located in the north of Quito, like PRAM and FENY near the area of the airport, have a fundamental frequency around 1 Hz. Station LILI installed at the southern part of the basin has a clear peak in the frequency 0.35 Hz. This frequency could be determined for the first time in Quito thanks to the sensor we have used (natural frequency of 0.2 Hz) and large time windows in order to have accurate results at these frequencies.

Stations BELL and CIRC present a good agreement between both methods, but no clear peaks. Stations in the basin, PRAM, FENY, and LILI, have a second peak of amplification around 5 Hz. This second peak is attributed to a surface layer of very soft clay (Guéguen et al. 2000). Station RUMP has a peak at a frequency close to 5 Hz.

It is interesting to note that the results obtained on H/V ratio can be easily compared with the ground motion simulations. Figure 4, for example clearly shows that the station in the south, LILI has large amplitudes at low frequencies (high periods) compared with the GMPE's. This low frequency amplification is also obtained from H/V methods. The behavior of RUMP station (high amplitude at low periods or high frequencies) is also very clear on the simulations. This is especially obvious for scenario 1 because the earthquake is far away, then the epicentral distances are equivalent for each stations. It is also favorable because the EGF frequency contents is broader for this scenario than for scenario 2, where the EGF is smaller, and then its low frequency content is maybe not significant.

6. CONCLUSION

An empirical Green's function method has been applied for the first time in the city of Quito. Two scenarios have been selected: a magnitude 7.1 event, 100 km away to the south, and magnitude 6 to 6.4 events very close to Quito. In parallel, H/V measurements have been realized on ambient vibrations using a broad band velocity sensor and on 12 earthquakes using the permanent accelerometer network.

Results of this study show that:
- A moderate size earthquake (Mw 6 to 6.4) in Quito could be devastating.
- A large earthquake in the Sierra, 100 km of Quito should not generate damages in the city.
- The variability from one site to another one is high.
- The H/V results obtained from ambient vibrations are comparable with the H/V results obtained from earthquakes.
- A low frequency amplification around 0.35 Hz has been detected on the stations at south, which may indicates that the basin is relatively deep under Quito.

Further studies and simulations are necessary to confirm these results. A combination between EGF's simulations and transfer functions should enable to obtain ground motions in the whole city.

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