Long period ground motion simulations at the Bogota basin, Colombia, based on a 3D velocity model of the basin from dense microtremors arrays measurements, gravity and geological data

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Abstract

Bogotá, a megacity with almost 8 million inhabitants is prone to a significant earthquake hazard due to nearby active faults as well as subduction megathrust earthquakes. The city has been severely affected by many historical earthquakes in the last 500 years, reaching MM intensities of 8 or more in Bogotá. The city is located at a large lacustrine basin extending approximately 40 km from North to South and East to West. The sediment infill of the basin is composed of very thick and soft clay deposits (up to 300 m in thickness) in wide areas of the basin, as well as alluvial deposits from rivers towards the South of the basin. We constructed the first 3D velocity model of the basin based on dense microtremors arrays measurements (radius from 60 cm to 1700 m) at 300 sites within the basin as well as single microtremors measurements at 800 points, which allowed us to estimate in detail the velocity model of the basin from the shallow deposits up to the seismic bedrock. Our dense single microtremors measurements in Bogota indicate that horizontal to vertical ratios of microtremors are characterized by large predominant peaks for periods as large as 4 seconds, near the center of the basin. To constraint the geometry of the basin we used available gravity data at approximately 400 points, as well as available geological information from boreholes within the basin. Our results show that the deepest point of the Neogene-Quaternary deposits reach a depth of 800 m with a bottom S wave velocity of 700 m/s. The seismic bedrock (Cretaceous sandstones, Vs=3000 m/s) reach a depth of 3800 m at the deepest point of the basin. We simulated three-dimensional long period ground motions at Bogota from a shallow crustal earthquake near the basin (2008/05/24, Mw5.9, depth 10km), using a discontinuous grid finite difference method. Our results show the generation of large amplitude and long duration surface waves at the basin in agreement with records of this earthquake at the strong motion network of Bogota.

Keywords: long period ground motions, 3D velocity model, microtremors arrays, gravity data, Finite difference method, Lacustrine basin, Bogotá

1. Introduction

Bogotá is located at the Eastern Andes range of Colombia at the North-West corner of South America. This region is within a complex tectonic setting resulting from the interaction of three lithospheric plates. The Nazca Plate converges from the west at a rate of ~54 mm/yr and the Caribbean plate is moving 20 mm/yr to the E-SE relative to the South American plate [1]. As a result of these tectonic stresses Colombia is transected by many quaternary fault systems within the Andes range [2,3]. Bogota city has been severely affected by many historical earthquakes from nearby faults, reaching intensities VII to VIII approximately once every 100 years [4].

Although seismic hazard in Bogota is essentially controlled by nearby crustal faults, the city has also experienced strong ground shaking from megathrust subduction earthquakes in the Pacific coast of Colombia in 1906 (Mw8.5) [5,6,7] and 1979 (Mw8.1) [8]. In August 24, 2008 a nearby shallow crustal earthquake (Quetame earthquake) was able to generate a fair amount of building damage in Bogota [9] despite its moderate magnitude (Mw5.9), highlighting the large contribution to strong ground motions from site amplifications at the basin [10]. The city is located at a large lacustrine basin extending approximately 40 km from North to South and East to West. Several microzonations studies have been undertaken in Bogota to date which have contributed to gain a very good knowledge on the geotechnical characteristics of the soils within the city [11,12]. However a detailed knowledge on the subsurface structure velocity characteristics of the Bogota basin was unavailable, due to the lack of dense geophysical measurements in previous studies, which are necessary to construct the underground 3D velocity model, and therefore improve our knowledge on the seismic hazard of the city. In this paper we applied state of the art methodologies for the estimation of the first 3D underground velocity structure model of the Bogota basin. We validate the velocity model by comparing our three-dimensional long period ground motions simulations with observed strong ground motions at the city from the 2008 Quetame earthquake. Our results show the generation of large amplitude and long duration surface waves at the basin in agreement with records of this earthquake.

2. Geological-geotechnical information of the Bogota basin

The Bogota basin is located at a high plain (2600m altitude) tropical montane region. The formation of the landscape at this region has been influenced by three factors, the uplift of the Andes (~3 to 5 Ma years), the formation of the tectonic-sedimentary Bogota basin (~3 Ma), and significant Quaternary glaciations (2.7 Ma) [13]. The basin was formed by a slow sedimentation process of fluvio-glacial deposits in the last 3 million years [14], which resulted in very thick Quaternary-Neogene lacustrine deposits (~600m of thickness), as well as alluvial deposits from rivers towards the South of the basin. The basin is bounded by Cretaceous sedimentary rocks (sandstones), which sharply outcrops from South to North towards the East of the basin (Fig. 1) [15]. Detailed stratigraphic information and absolute datings of the sediment infill in the basin was obtained from previous studies from a deep borehole at the center of the basin (Funza-II), reaching a Neogene formation at a depth of ~600 m (Tilatá formation) (Table 1) [14].
Soils in Bogota are largely composed of thick silty clays deposits in wide regions from the Central to the Northern part of Bogota (Fig. 4a). Towards the South of the city soil deposits are mainly composed of clayey sands and alluvial fan gravel deposits from rivers running from South to North of the city (Tunjuelo river and Bogota river). The hills sides to the East and South of Bogota are mainly composed of gravel hill side deposits, and claystones-sandstones rock outcrops. The geotechnical zonation map of Bogota in Fig. 4a was compiled from the latest microzonation report of Bogota city [12], only available in spanish.

3. Microtremors survey method

The microtremors survey method which is a very powerful tool to investigate the underground velocity characteristics of soil deposits has been widely used in many regions worldwide due to its low cost and accessibility [16,17]. In this study we performed microtremors array measurements to calculate the frequency dependent, phase velocity characteristics of Rayleigh waves of soil deposits (dispersion curves) [18,19], which are then used to estimate the velocity profiles below the arrays using a simplified inversion technique [20]. Microtremors measurements are performed using the layout shown in Fig. 2a. We use a configuration of four microtremors sensors located at the vertices and centroid of an equilateral triangle. Radius of the circle enclosing the triangle is variable from 60 cm (miniature array) to 1700 m (large array). Widely variable radius size of microtremors array measurements are intended to survey a broad range of wavelengths of phase velocities of Rayleigh waves from several meters to several kilometers, which allow us to estimate the underground velocity structure from the shallow soil layers [19] up to several kilometers to reach the seismic bedrock [21]. A typical miniature array microtremors measurement is shown in Fig. 2b. Microtremor sensors used for measurements are high dynamic range and extremely low self-noise tri-axial accelerometers produced by Hakusan Corporation (model JU410) (Fig. 2b). Due to their small weight (~3 kg) and easy operation they are very convenient for dense microtremors measurements campaigns.

We also investigate the predominant period of soils from the peak of horizontal over vertical spectral ratios of microtremors. This methodology has been extensively used worldwide as a very simple and useful index to characterize soil response [22].

4. Microtremors measurements

To investigate the velocity structure of shallow soil deposits we performed dense miniature microtremors array measurements at ~300 sites (one point every 2 km) to cover the entire urban area of Bogota city (Fig. 3a, red dots). Miniature microtremors array measurements are typically performed for a short observation time (15 minutes), which allow to easily perform many measurements in a short period of time. To investigate the velocity model of deeper layers (from several hundred of meters to several kilometers depth) we performed large microtremors arrays microtremors measurements (radius from 500m ~ 1700m) at 26 sites within Bogota (one point every ~5 km) (open circles in Fig. 3a), with the same triangular configuration as for miniature arrays but larger measurement times (up to two hours for the largest arrays) (Fig. 2a). Results of these measurements in Bogota are described in detail in section 5.
We also performed single microtremors measurements at ~800 sites in and around Bogota city (urban region of Bogota is enclosed by the black line in Fig. 3b) to investigate the predominant periods of soils in Bogota (Fig.3b). Our results indicate that horizontal to vertical ratios of microtremors are characterized by large predominant peaks for periods between 2 and 4 seconds, in wide areas from the central to northern part of Bogota (Fig. 3b and 4a). The longest periods of 4s correspond to very thick silty clay soil deposits (up to 300 m of thickness) towards the west of Bogota city. The southern part of Bogota is characterized by peak periods smaller than 2 seconds that gradually decrease to ~ 0.1 seconds as the measurements approach the hill sides of the city, where Claystone and Sandstones rocks outcrop (Fig. 1 and 4a). All our microtremors measurements were conducted in and around Bogota city, covering about half of the Bogota basin, which is the target of the 3D underground velocity model of this study. Futher studies of dense geophysical measurements are required to cover in detail the entire basin.

5. Estimation of 3D velocity model of Bogota

To construct a three dimensional underground velocity model of the Bogota basin to be used for long period ground motion simulations we combine information from velocity profiles obtained from our microtremors array measurements with gravity measurements, as well as the geological information from the deep borehole at the center of the Bogota basin (Funza-II borehole) [14]. We obtained S wave profiles at approximately 300 microtremors arrays measurement sites in Bogota (Fig. 3a and Fig. 4). As we can observe in Fig.4b the velocity profiles can be classified into three distinct groups based on their overall shape; the red profiles are characterized by having the smallest S-wave velocity values, the yellow profiles by the largest S-wave velocities and the blue profiles by having intermediate S-wave velocity values, for a given profile depth. On the other hand the red profiles are in average the deepest compared with the blue and yellow profiles. In Fig. 4a we can observe that the geographical locations of velocity profiles are in agreement with the overall characteristics of soil deposits in Bogota. Namely, red profiles correspond to the deepest and softest silty clay deposits, the blue profiles with the harder and shallower clayey sand deposits, and the yellow profiles to the claystone rock and hill-side gravel deposits (Fig. 4a).
Among all the S-velocity profiles obtained in this study, 45 profiles reached depths of several hundreds to 4 km (approximately at a 3 km spacing). Those are basically the ones used to image the velocity model for layers with S-wave velocities larger than 700 m/s. Our array measurements near the Funza-II borehole indicate that this is the value of S-wave velocity at the bottom of the borehole (-600 m), which corresponds to the maximum depth of the Quaternary-Neogene sediment infill of the basin (top of the Tilatá formation of Neogene age) (Table 1). We used this value as a reference to constraint the geometry of our velocity model at the bottom of the basin. In order to get a detailed geometry of the basin depth we also used dense gravity measurements at the Bogota basin (at 1 km spacing) performed during the first seismic microzonation project of the city [11] (triangles in Fig. 5). We filtered the original Bouguer anomaly data with a high pass filter with a cut wavelength value of 20 km to remove the regional topographic effects in the data (Fig. 5), and

then we interpolate the Bouguer anomaly residuals to obtain their values at the location of our S-wave velocity profiles within the basin. Finally we estimate empirical relationships between Bouguer anomaly residuals and the depth to several values of S-wave velocities from our profiles. As a result of this procedure in Fig. 6 we show those relationships for layers with S-wave velocity values of 700, 1000, 2000 and 3000 m/s (Fig. 6). We can observe that all our empirical relationships are characterized by large correlation coefficients, which demonstrates the ability of our datasets to fully characterize the 3D model of the basin. Using these empirical relationships we estimate the first 3D velocity model of the Bogota basin as shown in Fig.7 and Fig. 8. In Figure 7a we show the bottom depth of a layer with S-wave velocity of 700 m/s. This layer corresponds to the depth of the sediment infill of the Bogota basin. Near the Funza-II borehole location (Fig. 7a) the basin reaches it maximum depth at approximately 800 m. We can also observe that the basin has a complex depth geometry with sub-basin structures towards the North and West of Bogota city (Fig.7 and Fig. 8). Our model indicates that the basin is bounded by a sharp edge to the East (Fig.7 and Fig. 8), where cretaceous rocks outcrop at the eastern mountain range of the city [15], and the basin depth gradually decreases towards the South of the city. In Fig. 7b we show the bottom depth of layer with S-wave velocity of 3000 m/s (seismic bedrock). Near the Funza-II borehole the seismic bedrock reaches the maximum depth (3800 m) within the basin (Fig.7b).

6. Long period ground motion simulation of Bogota

We use our 3D velocity model of the basin to perform three dimensional seismic wave propagation simulations within the basin, using a discontinuous grid finite difference method (GMS) [23,24]. GMS is a very versatile tool to perform large-scale three-dimensional wave propagation simulations, as it allows for the use of a small grid size for regions with low S-wave velocities as within basins, and a coarser grid size for regions with large S-wave velocities. This grid scheme allows a significant reduction in the amount of memory required for computations.
We simulate the wave propagation from the 2008/05/24 Quetame earthquake (Mw5.8), which was a shallow (depth 10 km) strike-slip (left-lateral) earthquake that occurred 30 km SE of Bogota (Lon. -73.81, Lat. 4.40). Source model is assumed as a point source with a strike of 16, dip of 88 and rake of 174 degrees. The grid domain for the simulations spans an area of ~90 km by 100 km and a depth of 30 km, enclosing the Bogota basin as well as the epicenter of the Quetame earthquake (Fig. 1). We used a time step of ~0.008 sec (16000 time-steps), a grid size of 100 m for the region shallower than 4 km, and a grid size of 300 m for deeper regions. We also simulated ground motions at receivers within the Bogota basin and near the epicenter of the Quetame earthquake (black dots in Fig. 1). These points correspond to strong motion stations of the Strong Motion Network of Bogota (RNA) [25] and the National Strong Motion Network of Colombia (RNA), which recorded the Quetame earthquake. In Figure 9 we show the results of long period ground motion simulations (1 to 2 sec) at those strong motion stations. Our results show the generation of large amplitude and long duration surface waves at the basin in agreement with records of this earthquake.

7. Discussion and Conclusions

We conducted dense microtremors array measurements within the Bogota basin and estimated S-wave velocity profiles from the shallow soil deposits up to the seismic bedrock. We combine these results with available gravity measurements and a deep borehole, which are used to constrain the basin geometry, to estimate the first detailed 3D velocity model of the Bogota basin. Our results show that the bottom of the Neogene-Quaternary deposits of Bogota are characterized by an S-wave velocity of 700 m/s and reach a maximum depth of 800 m at the western part of the city. At this point the seismic bedrock (S-wave velocity of 3000 m/s) also reaches its maximum depth at 3800 m.
Using the velocity model of the basin constructed in this study we conducted large scale three-dimensional long period ground motion simulations of a nearby shallow crustal earthquake (2008 Quetame earthquake, Mw5.9), applying a discontinuous grids finite difference method (GMS). Our results show the generation of large amplitude and long duration surface waves at the eastern basin edge of our velocity model. These

results are in overall agreement with observed records of this earthquake at the strong motion network of Bogota. In this paper we modeled the sediment infill (Neogene-Quaternary deposits) of the basin as a single layer with an S-wave velocity of 700 m/s, to simulate long period ground motions. However we are aware that a lower velocity layer may be required at shallower depths to fully reproduce duration and amplifications of long and intermediate period ground motions. Also our velocity model of the basin need to be refined towards the western end (currently open), in order to have a better agreement with the total observed durations of ground motions, possibly due to trapped waves travelling across the basin. In a future study we will address those improvements of our velocity model of the basin.

8. Acknowledgements

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9. Copyrights

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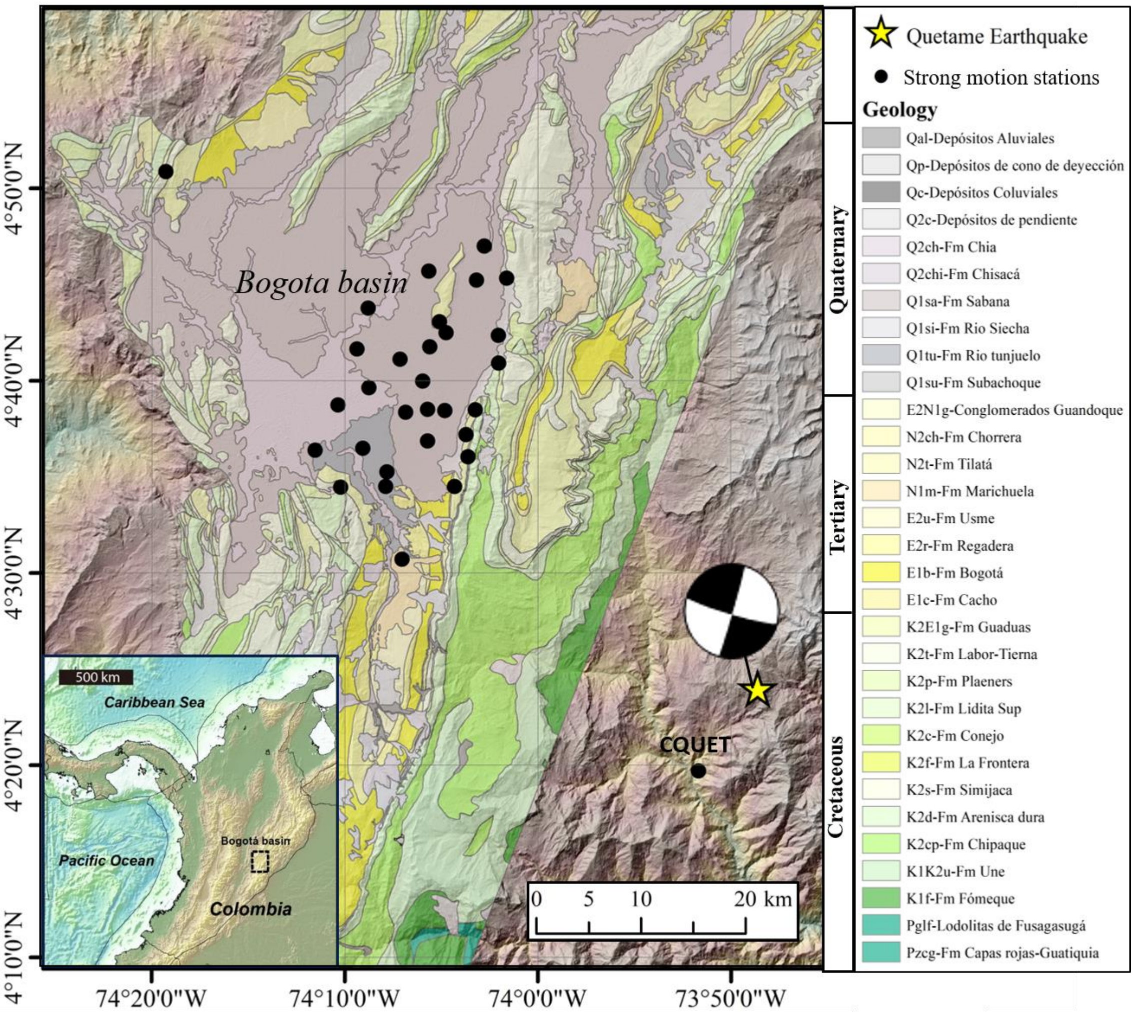

Fig. 1 – Geology of the Bogota basin. The focal mechanism solution of the 2008/05/24 Quetame earthquake (Mw5.9) is shown. The black dots correspond to strong motion stations in and around Bogota. Figure inset shows the location of Bogota basin in a map of Colombia.

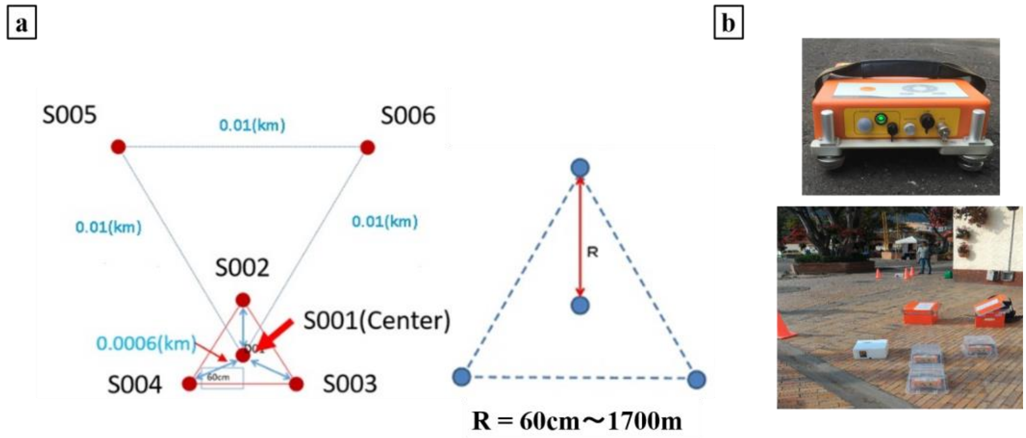

Fig. 2 – a) Layout of microtremors array measurements. Array radius ranges between 60 cm and 1700 m. b) Typical miniature array measurement in the Bogota basin (radius =60 cm).

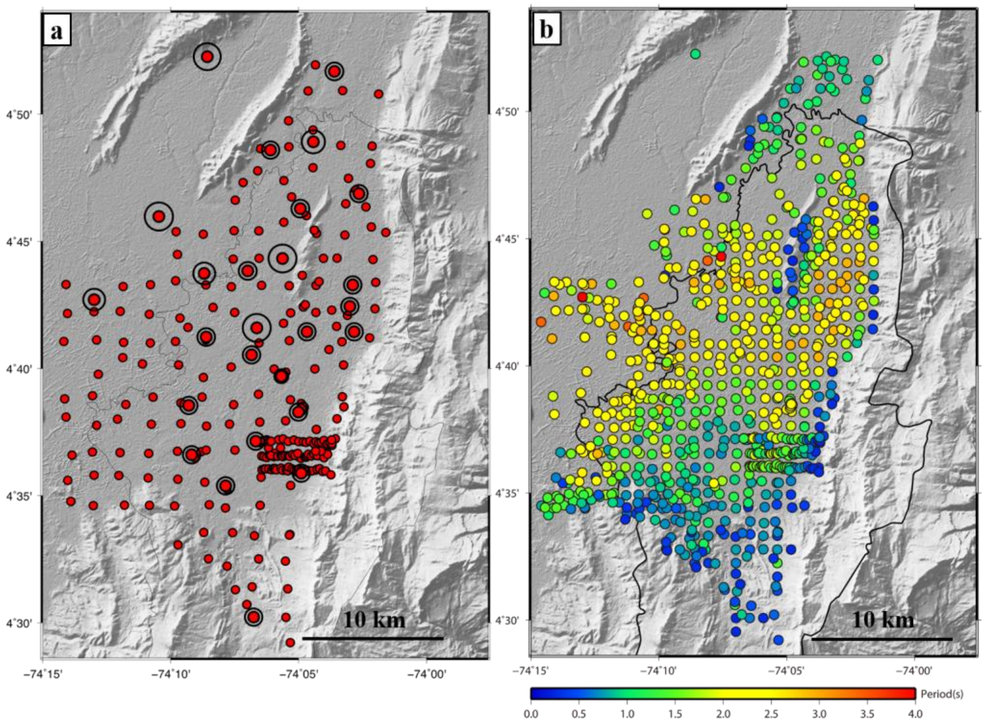

Fig. 3 – a) Microtremors array measurements in the Bogota basin. Red dots correspond to miniature to middle size array measurement sites (radius from 60 cm to ~100 m). The size of open circles correspond to large array sizes (radius from ~500 m to 1700 m). b) Single microtremors measurements points within the Bogota basin.

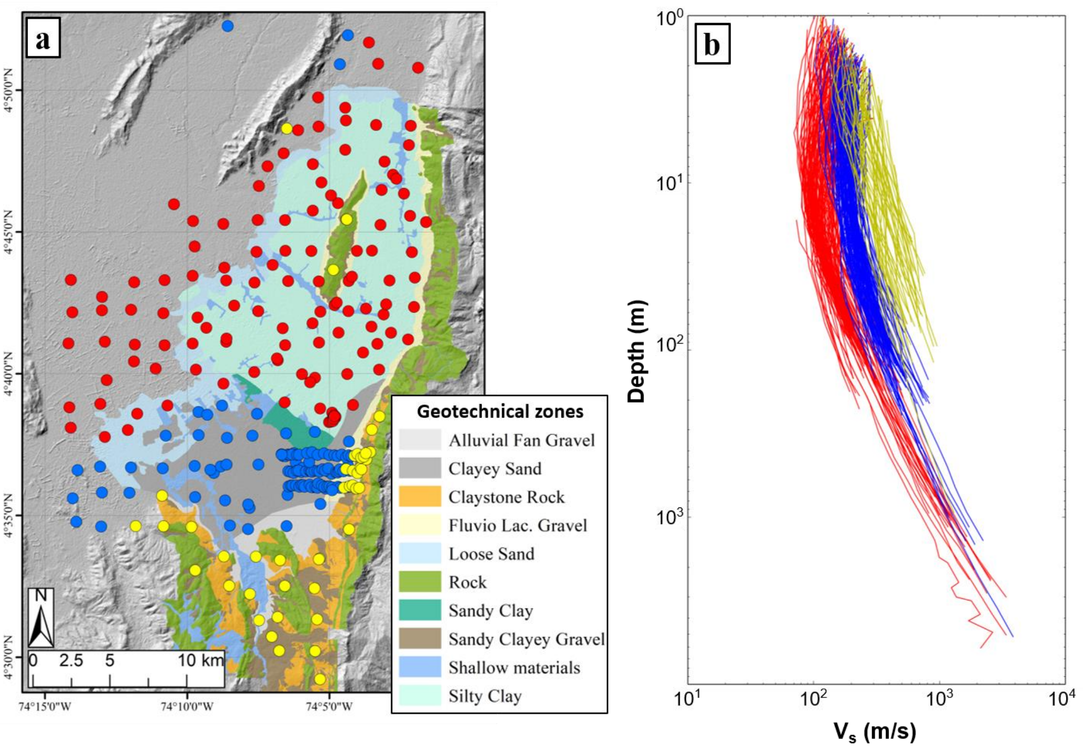

Fig. 4 – a) Location of microtremors arrays measurements (colored dots) overlaid on a geotechnical zonation map of Bogota. b) S-wave velocity profiles obtained from array microtremors measurements in Bogota basin. The colors of the velocity profiles correspond to the dots shown in the Bogota geotechnical map in a).

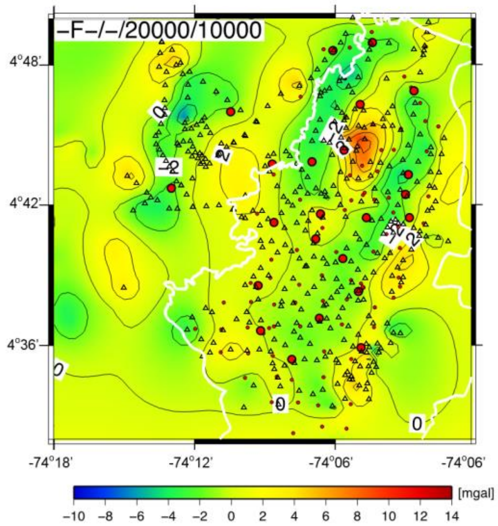

Fig. 5 – Bouguer anomaly residuals obtained from dense gravity measurements (shown as triangles) in Bogota basin. Bouguer residuals after low pass filtering Bouguer anomaly data below wavelengths of 20 km to remove effect of regional topography. Red dots show the microtremors arrays measurements locations used to estimate the 3D velocity model of Bogota.

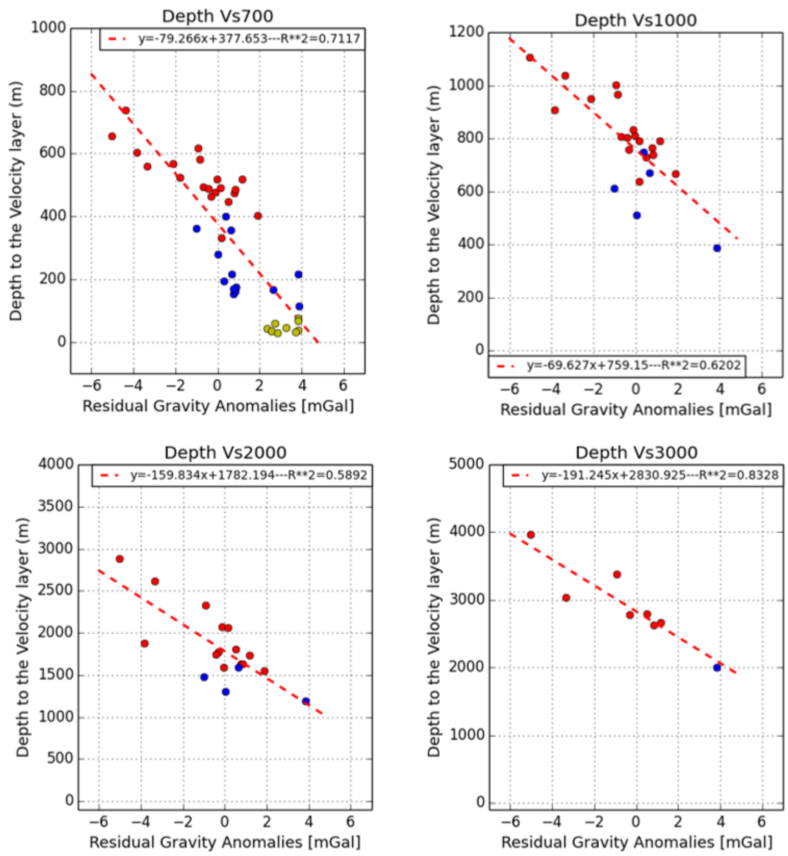

Fig. 6 – Empirical relationship between Bouguer anomaly residuals and bottom depth of layers with S-wave velocity of 700 m/s, 1000 m/s, 2000 m/s and 3000 m/s, obtained from velocity profiles from microtremors array measurements and Bouguer anomaly data.

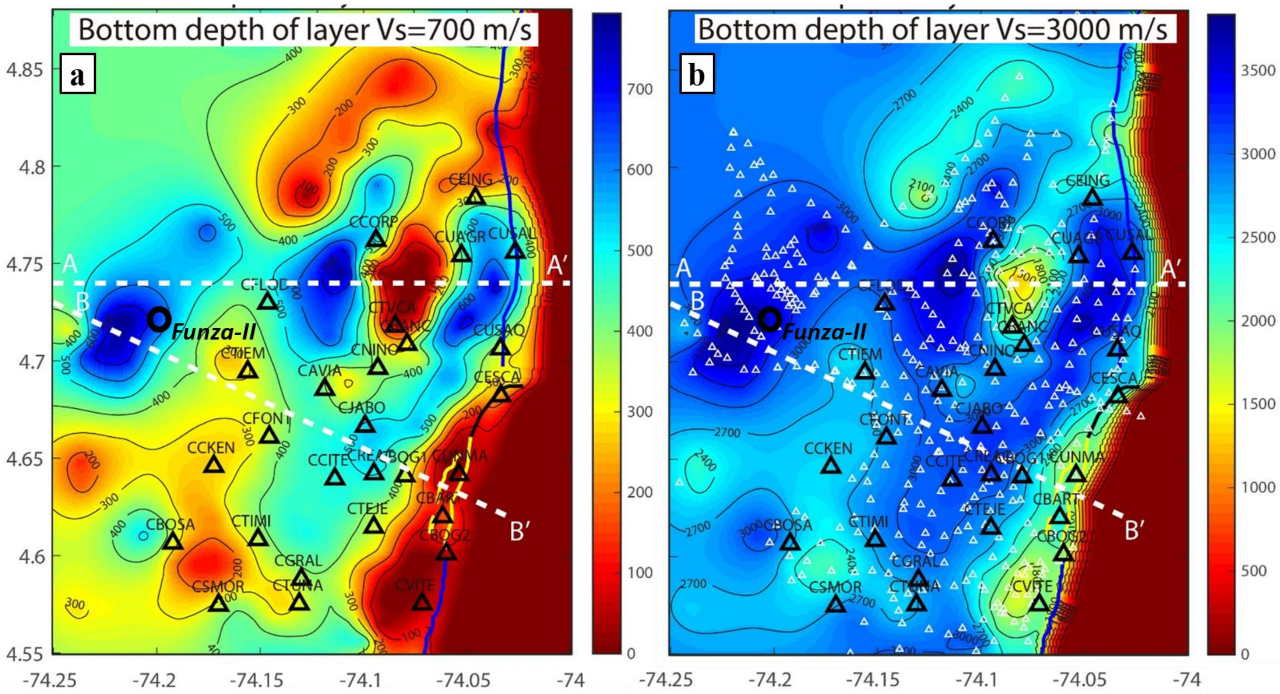

Fig. 7 –Map of bottom depth of S-wave velocity layer of a) 700 m/s and b) 3000 m/s, obtained from velocity profiles from microtremors array measurements and Bouguer residuals anomaly data (white triangles). Black triangles show the location of strong motion station within Bogota that recorded the 2008 Quetame earthquake. Location of Funza-II borehole is shown.

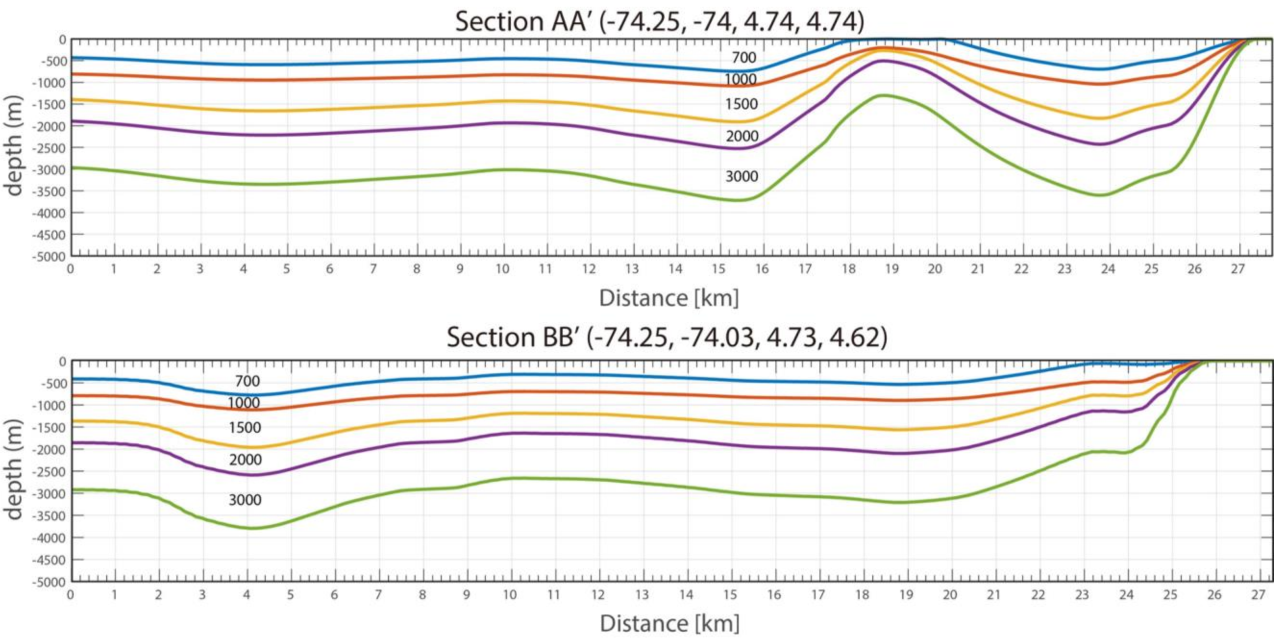

Fig. 8 – Cross sections of velocity models shown in maps in figure 7.

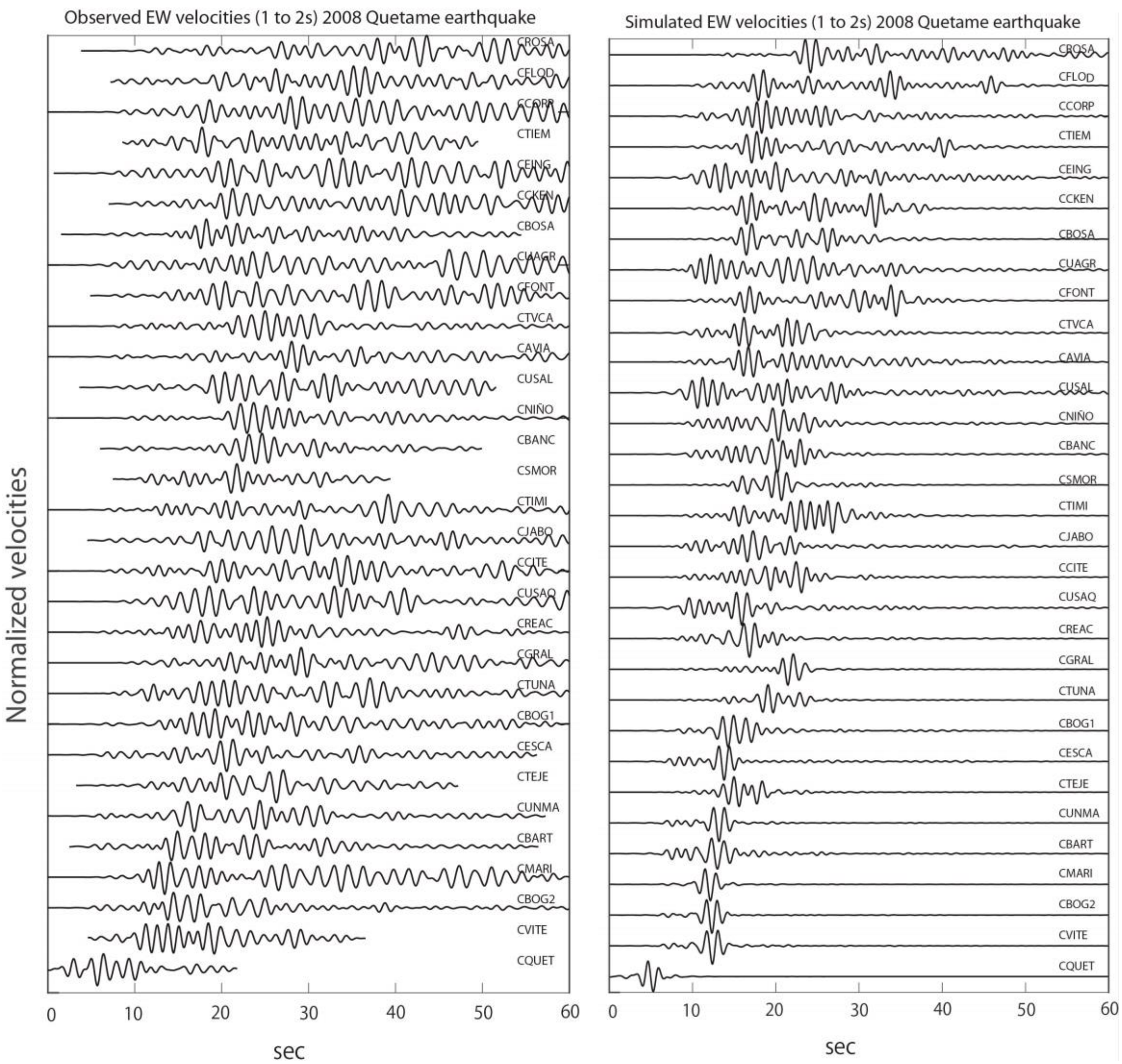

Fig.9 – a) Observed velocity waveforms at strong motion stations in Bogota (shown in Fig.1) during the Quetame 2008/05/24 earthquake. b) Simulated velocity waveforms at the same strong motion stations in a) from the Quetame earthquake.

Table 1 – Geological information of the Funza-II well

Layer top depth (m)	**Stratigraphy**	**Age**	**Formation**
0	Silty clays with peat and organic clays horizons	Middle Pleitocene (0~1Ma)	Sabana
325	Sandy clays with gravel, sand and peat horizons	Early Pleistocene to Pliocene (1~3.2Ma)	Subachoque
586	Clays and gravels Claystone	Early Pliocene (older than 3.2Ma)	Upper Tilatá

