16th World Conference on Earthquake Engineering, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 4614 (Abstract ID)
Registration Code: S-V1466044055

ESTIMATION OF VELOCITY MODEL OF BOGOTÁ BASIN (COLOMBIA) BASED ON MICROTREMORS ARRAY MEASUREMENTS

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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 also located at a large lacustrine basin composed of extremely soft soils which may strongly amplify the ground shaking from earthquakes. The basin extends approximately 40 km from North to South, is bounded by the Andes range to the East and South, and sharply deepens towards the West of Bogotá. The city has been the subject of multiple microzonations studies which have contributed to gain a good knowledge on the geotechnical zonation of the city and tectonic setting of the region. In order to construct a detailed velocity model of the basin we conducted 70 multi-sized microtremors arrays measurements (radius from 60 cm up to 1000 m) at 27 sites within the city. We calculated dispersion curves and inferred velocity profiles at all the sites. Our velocity profiles for the shallower sediments are characterized by a wide variability in Vs30 whose values range from 80 ~ 150 m/s in the northern and central part of the basin, and 120 ~390 m/s in the southern part. Our velocity models at the central part of the basin are characterized by a strong impedance at approximately 600m depth (Vs~2000 m/s), and reach the seismic bedrock (Vs~3000 m/s) at 3 km depth. However geological sections of the city suggest that the basin depth may significantly increase further west. Denser array measurement are required to investigate the detailed basin geometry.

Keywords: Strong motion, Bogotá basin, microtremors survey, seismic hazard, Colombia

1. Introduction

Colombia is located in the Northern Andes in a complex tectonic setting resulting from the interaction between three lithospheric plates. The Nazca (NZ) oceanic plate is converging eastward relative to the northwestern South America (SA) at 6 cm/yr and the Caribbean plate (CB) is moving 2 cm/yr to the E-SE relative to the South American plate (Veloza 2012, Pulido 2003) (Figure 1). As a result of these tectonic stresses Colombia is transected by many quaternary fault systems within the Andes range (Paris et al., 2000, Veloza 2012) (Figure 1). Seismicity from the subduction zones as well as from the continental crust is also very active (Pulido 2003). Four large magnitudes events (M>7) occurred along the subduction zone of the Ecuador-Colombia coast during the last century; In 1906 occurred the largest recorded event in the region (Mw 8.8) with a rupture length of approximately 500 km along the trench. This event was followed by three smaller events in 1942 (Mw 7.8), 1958 (Mw 7.7) and 1979 (Mw 8.2) that ruptured approximately the same area (Kanamori et. al., 1982, Beck and Ruff, 1984, Swenson and Beck, 1996) (Figure 1). In April 4, 2016 a devastating megathrust earthquake (Mw7.7) occurred in the Ecuador margin near the source area of the 1942 earthquake (Figure 1), highligtning the high seismic activity of the region.

Bogota city, located in the middle of the Andes range is prone to a significant earthquake hazard mainly due to nearby active faults, and the subduction megathrust earthquakes from the Pacific margin. The city has been severely affected by many historical earthquakes in the last 500 years, reaching MM intensities of 8 or more in Bogotá (Dimate et al., 2005). Bogota is also located at a large lacustrine basin composed of extremely soft quaternary soil deposits (INGEOMINAS, 1997) (Figure 2), which may strongly amplify the ground shaking from earthquakes. The basin extends approximately 40 km from North to South, is bounded by the Andes range to the East and South, and sharply deepens towards the West of Bogotá. Although the city has been the subject of multiple microzonations studies which have contributed to gain a good knowledge on its geotechnical zonation (INGEOMINAS, 1997, FOPAE, 2010), there is a deficient knowledge on the velocity model of the basin. In this study we aim to estimate the first detailed velocity model of the basin based on dense measurements of microtremors and continuous seismic observations within the city, as well as the geotechnical and geological information of the basin available from previous studies. These activities are a component of a multidisciplinary cooperative research project between Colombia and Japan entitled “Application of state of the art technologies to strengthen research and response to seismic, volcanic and tsunami events and enhance risk management in Colombia (2015-2019)”, sponsored by SATREPS, a joint program of the Japan International Cooperation Agency (JICA) and the Japan Science and Technology Agency (JST).

2. Microtremors survey method

The microtremors survey method is a very useful and popular tool to investigate the velocity characteristics of soil deposits and has been widely used in many regions worldwide (Okada 2003, Bonnefoy-Claudet et al. 2006), due to its low cost and accessibility. In this study we performed multi-sized microtremors array measurements to calculate the frequency dependent, phase velocity characteristics of Rayleigh waves of soil deposits (dispersion curves) (Cho et al. 2004, 2013), which are used to estimate the velocity profiles below the arrays using a simplified inversion technique (Pelekis and Athanasopoulos, 2011). Our array measurements radius span from several tens of centimeters to several hundreds meters to be able to recover a wide range of frequencies in the dispersion curves, and therefore to allow the detailed estimation of velocity profiles of soil from shallow to deep layers (several hundreds of meters). In order to estimate in detail the shallow velocity profiles (0~60m) we applied the “Miniature Array Analysis of Microtremors (MAM)” (Cho et al. 2013), which is based on measurements of microtremors using a miniature array consisting of seismometers placed at the center and circumference of a circle with several tens of centimeters of radius (Cho et al 2013). The MAM can reliably estimate velocity structures up to several tens of meters (Cho et al 2013), and only requires a very short measuring time (~15 min). These features make the MAM a very powerful tool for the quick and detailed estimation of the velocity profiles of shallow soils for wide regions, which can be used to obtain the distribution of widely used indexes of soil response such as AVS30 (time averaged S-wave velocity to a depth of 30m). For the estimation of deeper velocity profiles (up to several hundred meters) we analyzed the microtremors measurements from larger arrays with radius spanning from 5 m to 1000 m.

3. Microtremors measurements in Bogota

To investigate the velocity model of the Bogota basin, we performed 70 multi-sized microtremors array measurements at 27 sites within the Bogotá basin (Figure 2). Typical array configuration consisted of 4 sensors at the vertices and centroid of an equilateral triangle (Figure 3). Miniature array measurements (radius = 60cm) were performed at all sites. Small to medium size arrays measurements were also performed at most of the sites using the same array geometry and a radius up to 20m. Additionally, at two sites we performed large array measurements with radius up to 500 m and 1 km (black open circles in Figure 2). For all the measurements we used 4 tri-axial high dynamic range accelerometers (JU210) (Senna, 2011), manufactured by Hakusan corporation. For the largest radius arrays (R=500m and 1000m), we co-installed 4 servo velocity sensors (VSE-15D-6) manufactured by Tokyo Sokushin, beside the 4 accelerometers, and performed simultaneous microtremors measurements. The purpose of these measurements was to be able to reach longer periods of the dispersion curves. Measurements duration was typically increased with the array size from 15 min for the miniature arrays to about one hour for the largest size array. Sensors were covered with a plastic case to protect them from wind. A typical measurement for a miniature array is shown in Figure 3.

4. Periods of horizontal over vertical peaks in Bogota

We calculated the ratios of horizontal to vertical components (H/V) of microtremors at all measured points. Typical results of H/V are shown for two sites in Bogota (Figure 4). Our measurements show that periods of H/V peaks display a large variability within the Bogota basin, where values ranging from 0.1~0.3 s are observed near the outcrop of the Andes range to the east, values around 2 s are observed for most of the North and Central part of the city, and the periods gradually decrease towards the South (Figure 5). These peaks originate from the stack of layers above the engineering bedrock (Vs~400 km/s), which has been identified as the bedrock depth from previous microzonation studies (FOPAE, 2010) (contour lines in Figure 5). The engineering bedrock depth (dotted line in the geological cross section AA' in Figure 2), which approximately corresponds to the interface between quaternary soil deposits (Q units) and Terciary/Cretaceous layers (T and K units) (Figure 2), was estimated in those studies as deep as 400 m and may be deeper towards the west of the city.

5. Estimated velocity profiles in Bogota

As outlined in section 2 microtremors array measurements are used to estimate the dispersion curves of Rayleigh waves and estimate the velocity profile of S-waves. Two examples of these calculations where array measurements for all sizes were performed, are shown in Figure 6 a,b. In Figure 6a we show the dispersion curve and S-wave velocity profile inferred in site CBOG1, within the campus of the National University of Colombia. At this site we performed six array measurements using the sensor geometry outlined in section 3 and setting the array radius to 60cm, 10m, 30m, 50m, 150m, and 500m. Period of H/V peak at this site is 2.04s. The velocity model is characterized by a strong impedance at approximately 600m depth (Vs~2500 m/s), and reach a Vs~2000 m/s at ~2 km depth. In Figure 6b we show the dispersion curve and S-wave velocity profile inferred in site CJABO, within the Simon Bolivar park. We performed six array measurements at this site using the sensor geometry outlined in section 3 and setting the array radius to 60cm, 20m, 40m, 100m, 300m, and 1000m. Period of H/V peak was 2.27s. The velocity model is characterized by a strong impedance at approximately 500m depth (Vs~2000 m/s), and reach the seismic bedrock (Vs~3000 m/s) at ~3 km depth. Following the same procedure we estimated the S-wave velocity profile at other 25 sites for arrays with smaller radius (from 60cm to ~30m).

6. AVS30 distribution in Bogota

Using the results of all S-wave velocity profiles inferred in this study, we calculated the time averaged S-wave velocity to a depth of 30m (AVS30) for all measured sites. Distribution of AVS30 values within Bogota are characterized by a wide variability, ranging from 80 ~ 150 m/s in the northern and central part of the basin, and 120 ~390 m/s in the southern part. Our results indicate a strong change in AVS30 between the northern and the Southern parts of Bogota (colored dots in Figure 7). This striking difference appears to have a strong correlation with the distribution of water content of shallow soils within Bogota obtained by the latest microzonation study of the city (FOPAE, 2010), where shallow soils are characterized by a very large water content in Northern Bogota (clays and silts), as compared to the small water content of soils towards the South of Bogota (gravels and sands) (depicted in a yellow to blue color scale in Figure 7).

7. Conclusive remarks

We investigated the velocity model of the Bogota by performing 70 multi-sized microtremors array measurements at 27 sites within the basin (array radius of tens of centimeters to hundreds of meters). Our velocity profiles for the shallower sediments of Bogota are characterized by a wide variability in Vs30 whose values range from 80 ~ 150 m/s in the northern and central part of the basin, and 120 ~390 m/s in the southern part. Our results indicate a sharp boundary in shallow S wave velocities between very soft sediments North of the basin and harder sediments to the South. This striking difference appears to have a strong correlation with the very large water content of the shallower soils (clays and silts) to the North as compared to the small water content of soils (gravels and sands) to the South. Our velocity models at the central part of the basin are characterized by a strong impedance at approximately 600m depth (Vs~2000 m/s), and reach the seismic bedrock (Vs~3000 m/s) at 3 km depth. However geological sections of the city suggest that the basin depth may significantly increase further west. Our initial results indicate that our microtremors survey technique using state of the art equipment and methodologies is very useful to estimate the velocity structure of the Bogota basin. Denser array measurements and further detailed calculations are required to investigate in more detail the velocity model of the basin.

8. Acknowledgements

These activities are a component of a multidisciplinary cooperative research project between Colombia and Japan entitled "Application of state of the art technologies to strengthen research and response to seismic, volcanic and tsunami events and enhance risk management in Colombia (2015-2019)", sponsored by SATREPS. We would like to thank all members of our SATREPS team involved in the present study; Monica Arcila, Diana Arevalo, Ivan Bautista, Luisa Castillo, Cristian Gonzalez, Andres Hernandez, Jessica Luengas, Mario Leal, Elizabeth Mayo, Julian Montejo, John Mora, Leonardo Quiñones, Gustavo Redondo, Andrea Riaño, Marta Tovar and Luis Yamin, as well as the cooperation of Ikuo Cho.

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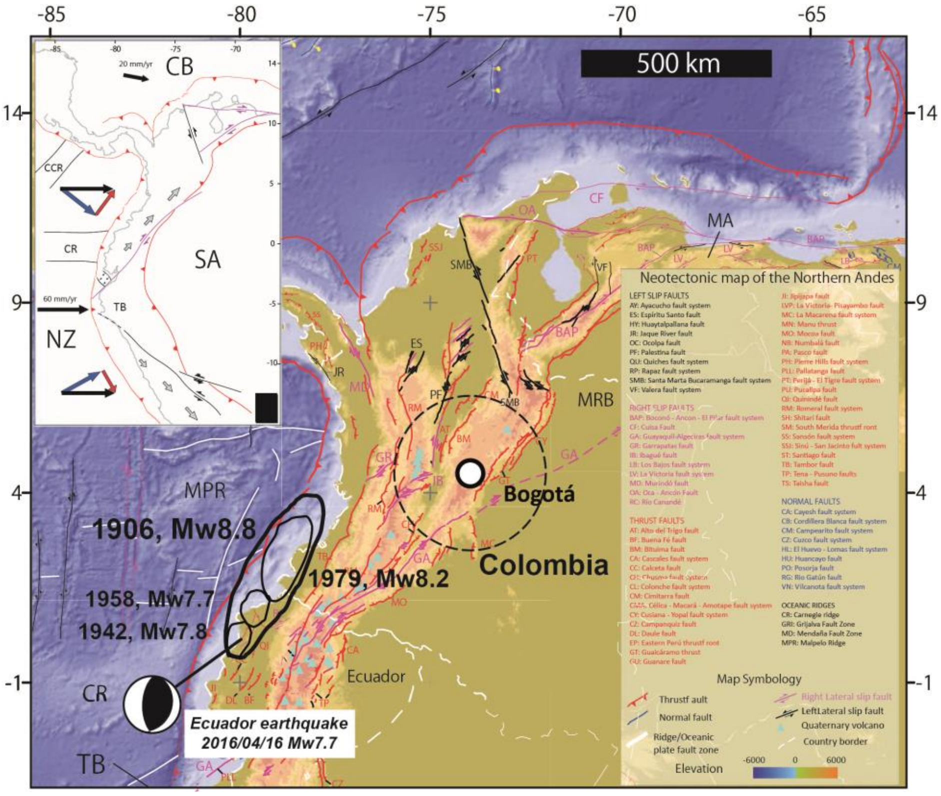

Fig. 1 – Tectonic setting of Colombia (after Veloza, 2012)

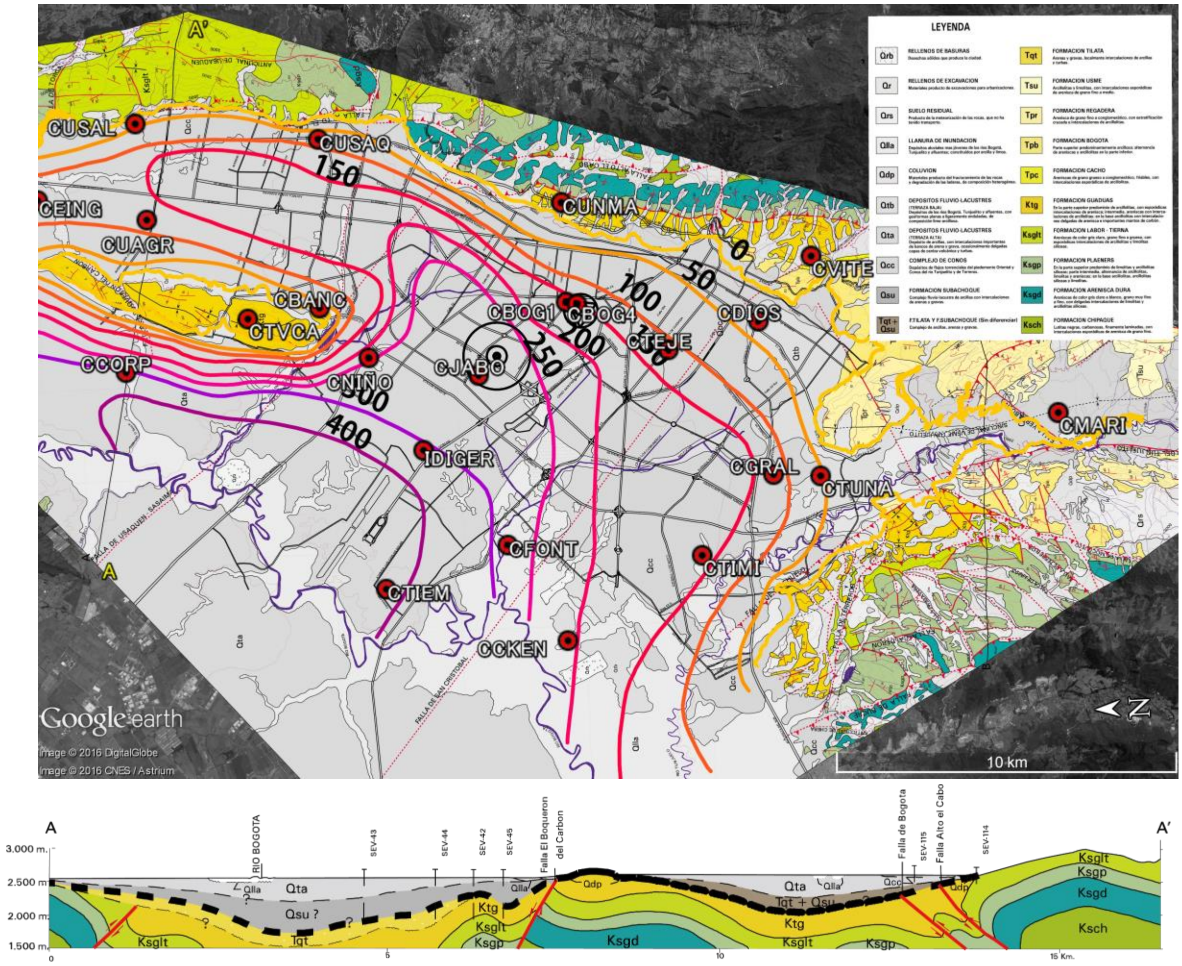

Fig. 2 – Measurement sites of microtremors arrays in this study, overlaid on a geological map of Bogota (INGEOMINAS, 1997). Contour lines denote the bedrock depth (in meters) according to a microzonation study of Bogota (FOPAE, 2010). Black open circles denote the large array measurements (2 sites). (a) Geological section of Bogota across AA' (INGEOMINAS, 1997) (b)

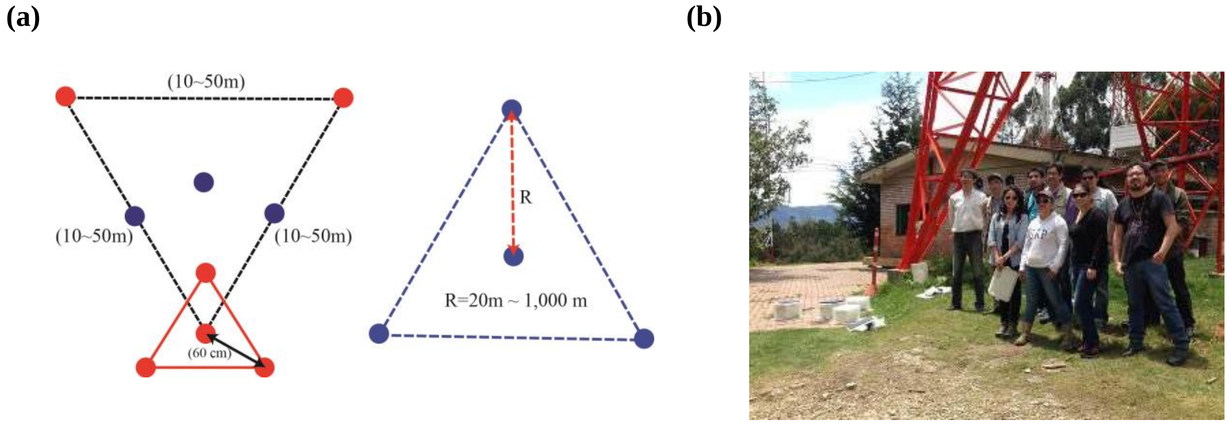

Fig. 3 – Layout of microtremors arrays measurements for miniature, small and medium and large size arrays (a). Typical miniature microtremor array measurement (b).

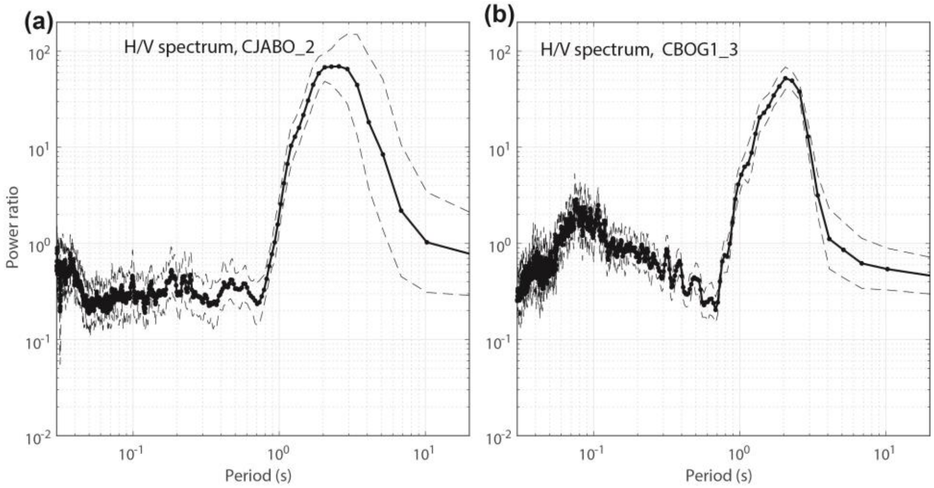

Fig. 4 – Average and +/- 1 σ of power spectrum of H/V (continuous and dashed black lines respectively), from multiple microtremors measurements within site CJABO_2 (a) and CBOB1 (b).

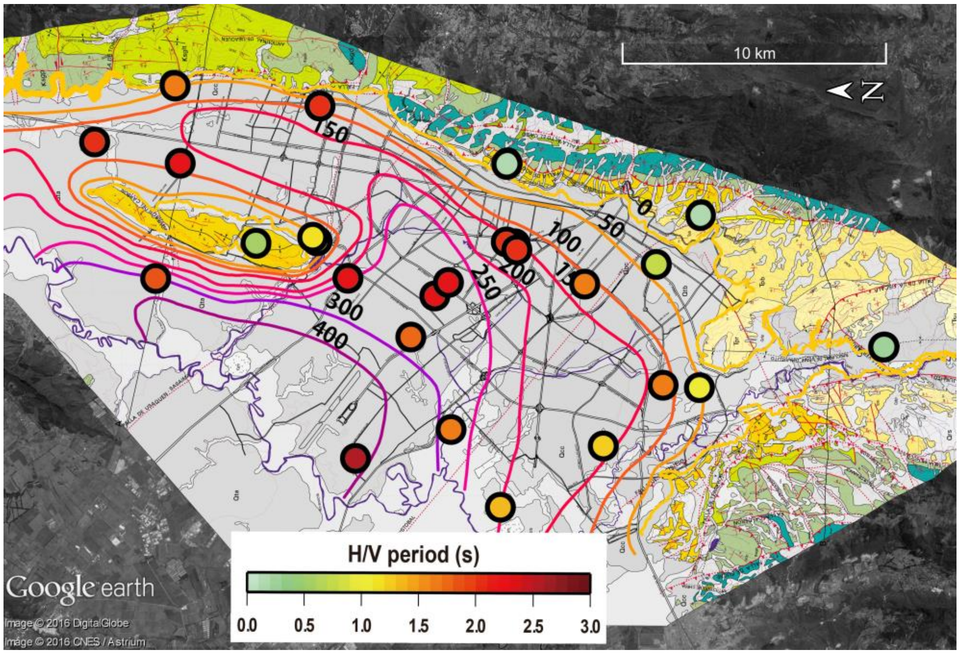

Fig. 5 – Distribution of H/V predominant peaks in Bogota.

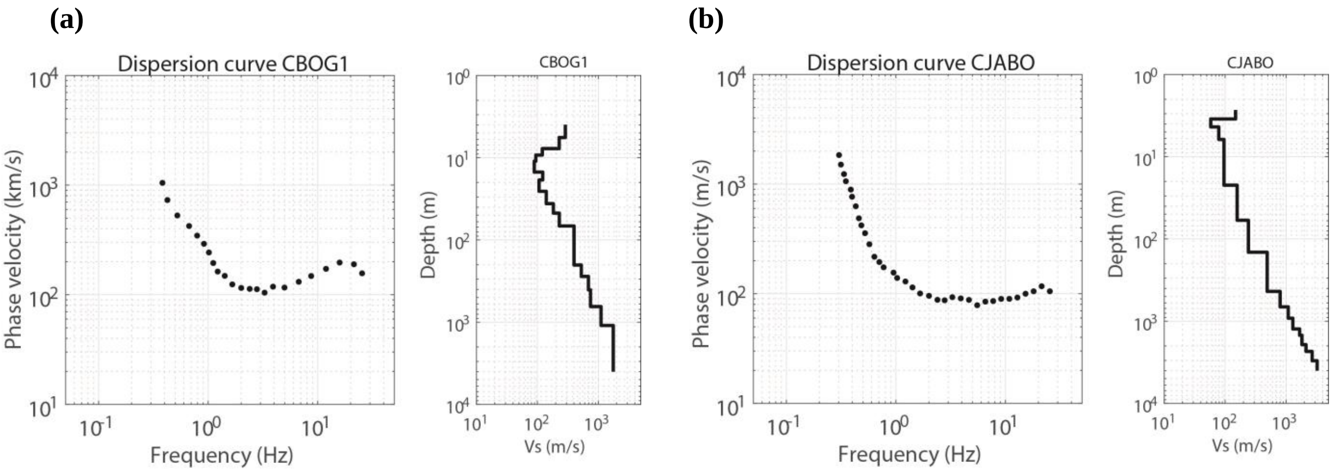

Fig. 6 – Dispersion curve of surface waves and velocity model estimated from multi-sized microtremors arrays measurements at CBOG1 (R = 60 cm,10m, 30m, 50m, 150m and 500m) (a), and at CJABO (R = 60 cm, 20m, 40m, 100m, 300m and 1000m) (b).

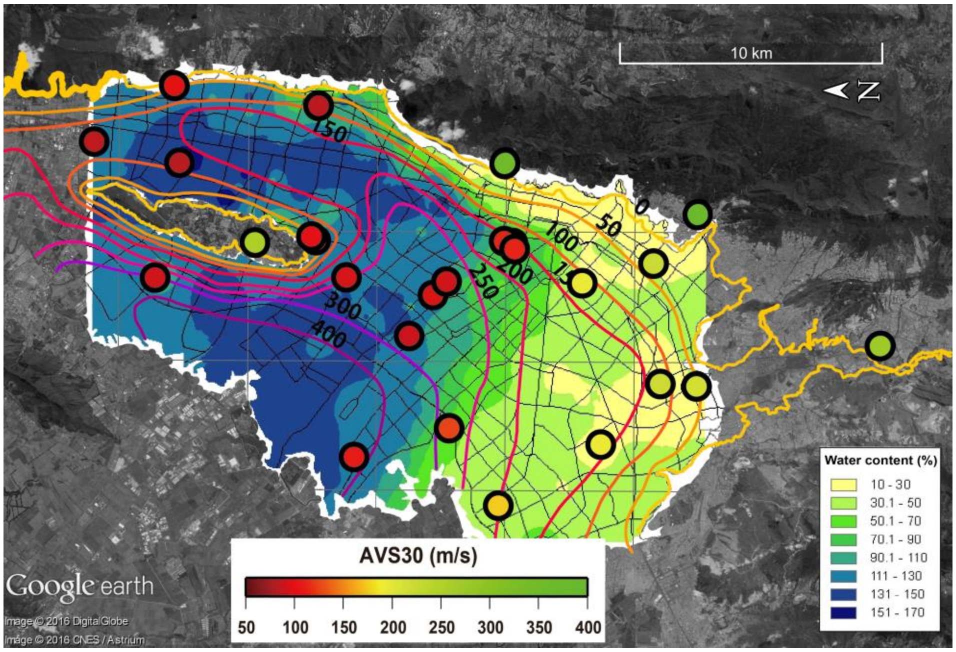

Fig. 7 – AVS30 in Bogota calculated from S-wave velocity models obtained in this study at all array microtremors measurement sites (points colored from dark red to green), overlaid to the distribution of water content of soil within Bogota (color scale from yellow to blue) (FOPAE, 2010), and basin bedrock depth contours (FOPAE, 2010).