Ambient Seismic Noise: a continuous source for the dynamic monitoring of landslides

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Abstract: Rainfall-induced variations in pore water pressures are the most common sources of significant disasters involving soils like landslides and structural collapses of man-made infrastructures. This study aimed at communicating preliminary results of seasonal monitoring of the Sobradinho landslide, Brasilia, Brazil, using ambient seismic noise. The noise was recorded before, during and after the rainy season with three L4-3A seismometers (2Hz) installed in a triangular array within the landslide mass. These records were processed using horizontal to vertical spectral ratio (HVSR) technique. As it is resulted from the performed analyses, two frequency (ubiquitous (2Hz) and iniquitous (>2Hz)) peaks were observed over HVSR curves. The fluctuations in the secondary peak of HVSR curves are possibly related to changes in soil properties of landslide mass (i.e. saturation, water content, consistence) in response to seasonal meteorological conditions. Experiments with a denser observation system are required to validate such a behavior. The proposed method can be used for the monitoring of landslides as well as civil engineering structures like dams, enbankments, backfills.

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Introduction

Major disasters in Brazil are flooding, landslides, and dam failure. Brazil has witnessed the worst disasters of the 21th century in the form of the Fundão tailings dam sudden failure on November 2015 in the absence of any substantial magnitude earthquake as well as of the Brumadinho dam on January 2019. The failure were caused by an already weakened state of the dam wall. Continuously monitoring for structural stability is required to avoid such disastrous events in future (Olivier et al. 2017 and references therein).

The landslide has a more significant share of the Brazilian physical hazards. There is shallow rainfall triggered landslides in Brazil. From 1988-2015 period, there were 733 landslides events in 243 municipalities, with 4.000 fatalities. Economic losses, homelessness are the other impacts of these hazardous events, especially in states of Rio de Janeiro, Sao Paulo, Minas Gerais and Santa Catarina. The tragedies of 1966, 1967, 1985, 1988, 1995, 2008, 2009, 2010, 2011 and 2014 are the historical reminder of the atrocities caused by the rainfall triggered shallow landslides (Martins et al. 2018 and references therein).

The landslide studies carried out in Brazil until now are of three broad categories as 1) index based susceptibility mapping, 2) geomorphological analysis and 3) soil geotechnical parametric estimation by in-situ testing. According to the best of author's current knowledge, no study dedicated to the application of ambient noise based geophysical techniques for the understanding of dynamics of unstable slopes in the region.

In this framework where continuity and high resolution are desired, ambient noise based monitoring techniques are recommended. A generic term used to define the ambient vibrations of the ground caused by sources such as tide, turbulent wind, effects of wind on trees or buildings, industrial machinery, cars, and trains, or human footsteps is called noise. Based on the frequency contents, there are two sources of noise as natural and cultural commonly referred to as microseisms (< 1Hz) and microtremors (> 1Hz), respectively (Hussain et al. 2017). During last decades or so, the common applicabilities of these techniques have increased exponentially. Some applications on hill slopes are: (1) resonant frequency estimation by HVSR at rock slope (2) dispersion curve of surface waves and shear wave velocity profile at active earthflow slope using a small aperture array (3) amplification and resonant of rock slope by the noise polarization analysis (4) noise topographic methods for the determination of landslide mass velocity structures.

The primary goal of this study is to understand if the seasonal dynamics of a Sobradinho landslide in Ribeirão Contagem River basin can be deduced from a change in dynamic properties or in behavior of the landslide mass. HVSR noise measurements were taken at three different locations on the landslide mass, before during and after the rainy season in order to see the possible effects of seasonal changes on the frequency response of the landslide mass.

Methodology

The Contagem watershed has an area of 146 km^2, is located in the northern part of the Federal District of Brazil in the Sobradinho administrative unit. The Maranhão River is the primary tributary of the watershed that flows in the north-northeast directions. The slope chosen for this work is located in the cow and horse farm in a small vicinity

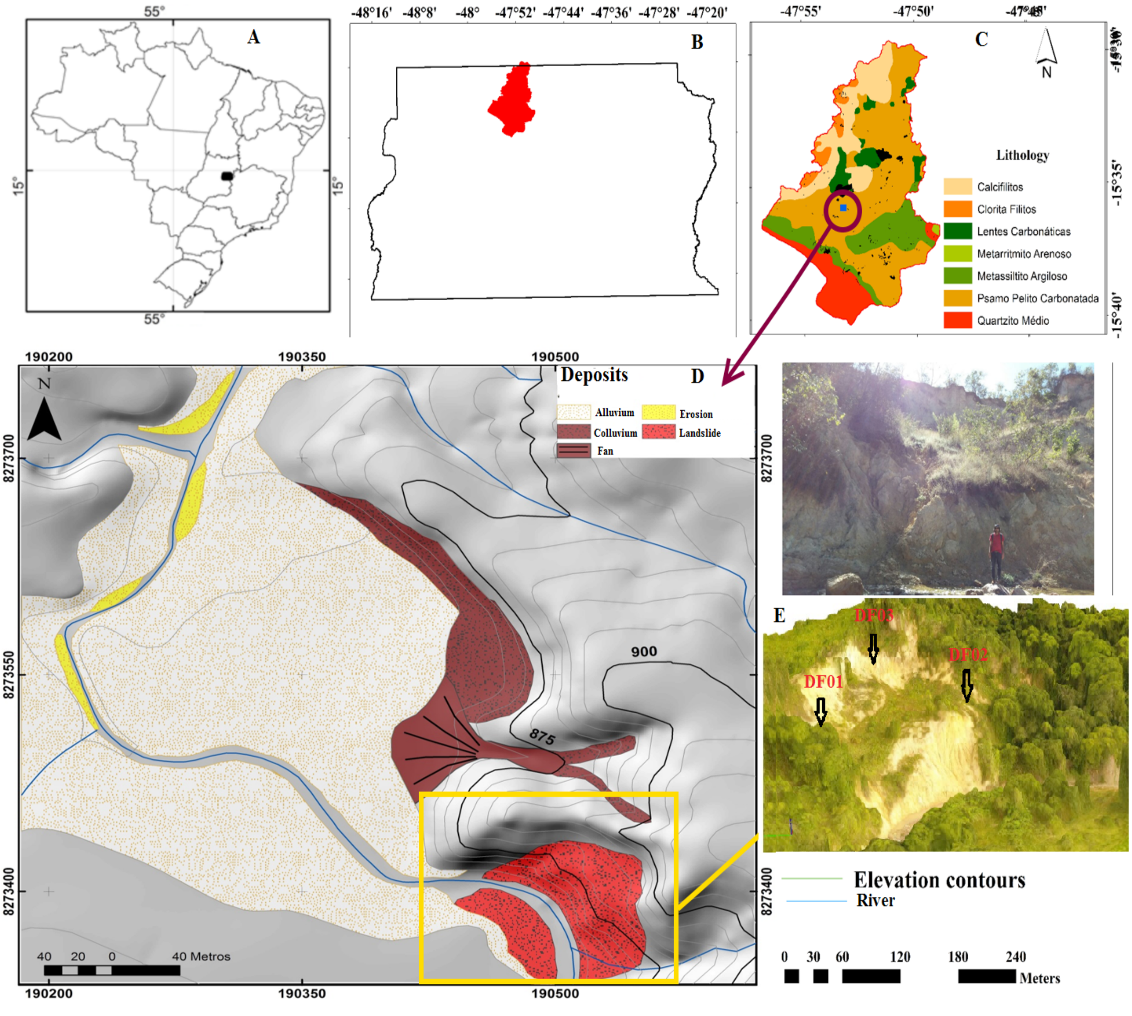

Figure 1. (A) Location of Federal District on the map of Brazil, (B) location of Ribeirão Contagem watershed on Federal District and (C) lithological units of the watershed. (D) Geomorphological units, (E) zoomed view of the landslide showing the seismic sensor locations (inverted arrows).

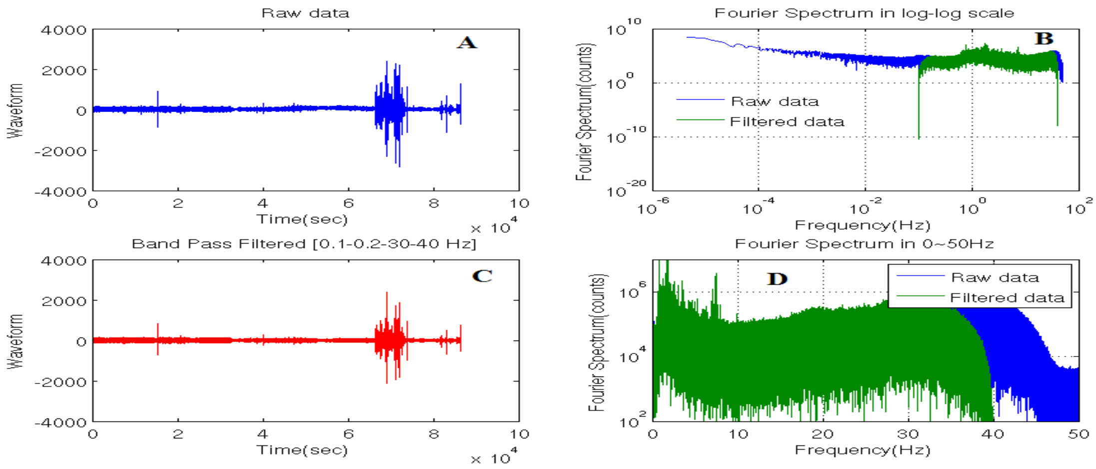

Figure 2. (A) Raw noise record at Z-component of station DF01 during dry conditions. (B) Fourier spectrum on a log-log scale, (C) data is bandpass filtered, (D) Fourier Spectrum in 0-50 Hz range.

naming "Rua da Matto" (Figure 1). In the studied area outcrop metasedimentary rocks of Proterozoic age that were deformed during the Brasiliano Cycle (650 My) covered by a thick weathering mantle (Zoby, 1999). The climate in the area is semi-humid tropical with a rainy summer and dry winter. The mean annual precipitation in the area is 1,442.5 mm (Hussain et al. 2017 and reference therein).

Noise acquisition system consisted of deployment of 3 Sercel L-4A-3D short period seismometers with a natural frequency response of 2 Hz. The data was recorded in a continuous mode at a sampling rate of 250 sample per second (SPS) with DASS-130 RefTek dataloggers. Raw ambient noise recorded at DF01 is shown in Figure 2. In the first step the night time records frm 01 to 06 hours were merged in SAC software then HVSR were calculated in Geopsy software (http://www.geopsy.org/).

The single-station horizontal to vertical ratio (HVSR) technique (Nakamura, 2008), where a single three-component station is used for the noise recording, is based on the assumption that there is no material changes in the horizontal extent and changes are only considered due to vertical variation in the deposits, i.e. a 1D model of a multi-layer soil column overlying a seismic bedrock. The theoretical bases of this technique are still in debate. Different theories has been proposed based on the presence of surface and body waves in microtremor. First view point has linked HVSR peak with ellipticity of Rayleigh waves around the fundamental frequency of site provided that there exist a sharp impedance contrast between the soil and bedrock (Bard, 1999). In second view the HVSR ratio peak is considered to be related with the transfer function of vertical polarized SH waves (Nakamura, 1989). The third view point is based on the assumption of diffuse wave field, where the microtremor is treated as a diffuse field which contains both surface (Love and Rayleigh) and body (P and S) waves (Sánchez-Sesma et al., 2011).

The one is that explain HVSR as frequency dependent Rayleigh ellipticity, is the most adopted theory that explain HVSR technique (Gasper, 2017 and references therein). It is based on the assumption that vertical component amplitude is relatively insensitive to the site effects and is mainly representative of the source and attenuation effects. In order to remove the effects of source and attenuation path from the horizontal component (contains Rayleigh and Love waves), it is divided with the spectral amplitude of vertical component that results in HVSR curve as a function of frequency. This amplification of the horizontal component is related to Rayleigh wave ellipticity affected by the soil induces modification. This ellipticity is prominent due to high impedance contrast between soil and bedrock. The impedance contrast appears because of vanishing of spectral energy at the vertical component and inversion of rotation of fundamental mode (Hussain et al. 2017). This information about the resonance frequency of sediments is provided without any previous knowledge of the geological and S-wave velocity structure of the subsurface (Gasper, 2017).

The modal frequencies and the corresponding dynamic response is related to the changes in the stiffness of a geological material mainly because of the seismic history or environmental conditions.

Along with these changes in mechanical properties, the boundary condition between bedrock and remolded soil (shear zones or sliding surface of a landslide) can also alter the modal frequency or its amplitude.

In order to understand the effects of local noise sources (traffic, mining and anthropogenic activities), directional analysis (amplitude and spectrum rotates) is done. The amplitudes and spectrum of HVSR curves are rotated at 10-degree azimuth, starting from 0 to 180 degree. These rotates will show the behavior of HVSR at all directions, if it is same at all azimuths (ideal condition) it confirm that the ground structure are 1-D (variations only in one direction) and noise wave field is homogeneous, and there are minimal effects of the noise sources.

Results and Discussions

As it resulted from HVSR curve plots obtained at the Sobradinho landslide site, two frequencies peaks, one at 2 Hz and second at greater than 2Hz are observed (Figure 3). The ubiquitous frequency (2Hz) is the frequency of Saprolite layer over the bedrock and is not affected by the changes of the degree of saturation due to rainfall events (Hussain et al. 2017; 2018). The second peak is related to landslide and variations in this peak are observed because of the change in soil properties.

During saturated conditions, the frequency is 8 Hz (Fig. 3). From this frequency, the time-period of landslide mass can be calculated as the inverse of frequency. The period can be used to model these effects on the overall mobility of landslide mass. However, there are slight variations in amplitudes of both frequency peaks which are also related to the changes in the dynamism of landslide mass. From the polarization analysis (HVSR and amplitude rotate) it is clearly visible that the ubiquitous peak (2Hz) is not polarized while high-frequency peak seems to be polarized (Figure 3). The future analysis will be dedicated to resolving this secondary peak polarization.

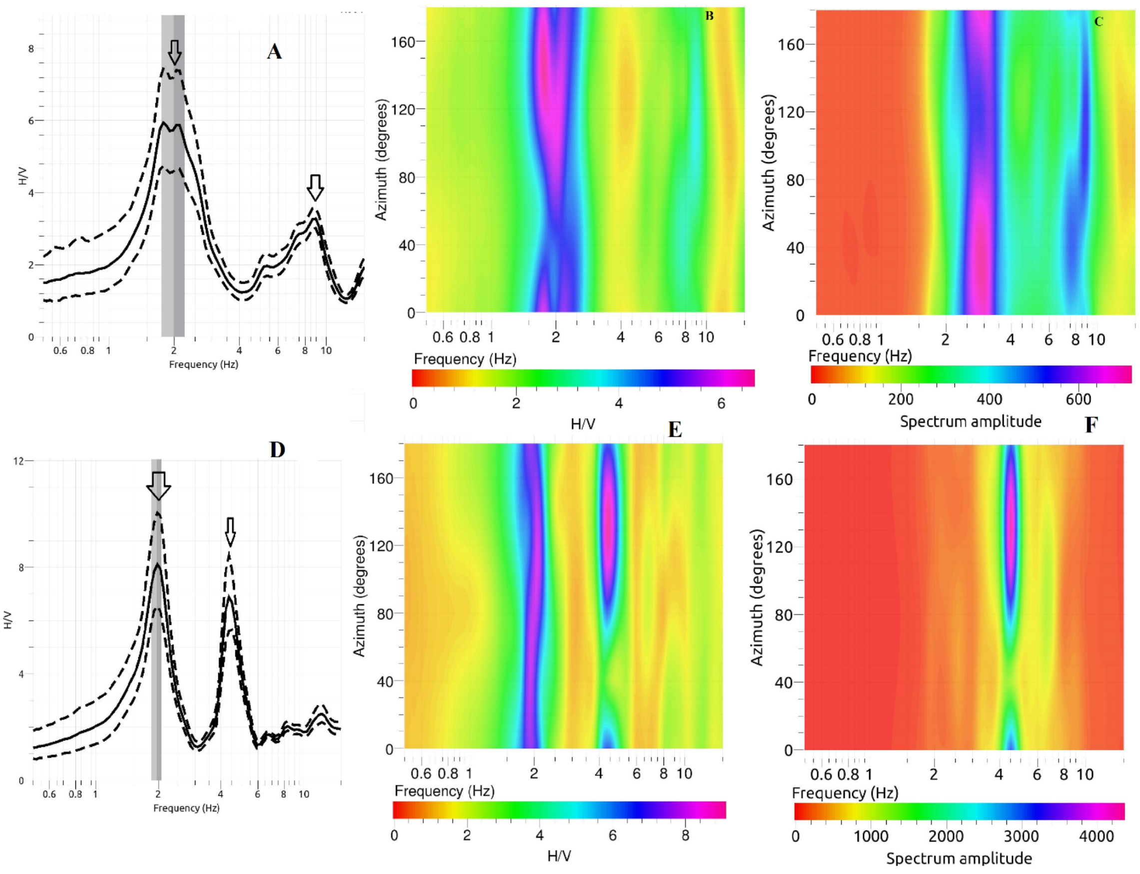

Figure 3. Seasonal response of HVSR (dashed lines are a standard deviation, and solid lines are average) curves at station DF03 (A: saturated condition, D: dry condition). Resulting HVSR and spectrum rotate of DF03 (B, C, E, F). The peak at 2Hz is a stratigraphic peak while the second peak at higher related to the is landslide mass.

Conclusion and Recommendations

The present study is a preliminary step that will lead to a comprehensive application of geophysical techniques for hazard assessment. Further studies will allow to better understand implications of rainfall events on the seismic response at Sobradinho landlside site due to changes in soil properties. The here obtained results output that the peak of HVSR curve is sensitive to the seasonal variations in landslide mass. Future analyses will focus on highlighting noise properties changes to be related to the variation of physical properties in the landslide mass (i.e. due to soil saturation after rainfalls). The here experienced methodology can be applied to monitoring dams and other soil-made infrastructures by monitoring changes in natural resonance periods that could occur over time as an effect of the damaging induced by disturbing factors. The changes in natural period could be also modeled by numerical codes.

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