SR, Seismic Refraction; ANT, Ambient Noise Tomography; SI, Seismic Interferometry; EGF, Empirical Green Function; SASW, Spectral Analysis of Surface Waves. Martín Cárdenas-Soto, School of Engineering, Geophysical Department, National Autonomous University of Mexico, 04510 Coyoacán, Mexico City, Mexico martinc@unam.mx School of Engineering, Geophysical Department, National Autonomous University of Mexico, 04510 Coyoacán, Mexico City, Mexico
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Seismic refraction and ambient noise methods to explore the extension of soft materials in a landslide

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Abstract

A portion of the west of Mexico City is a densely populated area located in an abrupt topography, whose volcano-sedimentary materials increase the likelihood of landslides. This study uses Seismic Refraction Tomography (SRT) and Ambient Noise Tomography (ANT) methods to estimate the extent of landslide-prone materials at a test site. We exploited the geometry of a quadrangular array of surface sources and receivers to generate a Vp tomography image of the bedrock and surface-wave group-velocity tomographies of SRTand ANT in the frequency range of 6 to 26 Hz. We found that the best velocities correlation between the two methods is an average frequency of 24 Hz. The results show the areas of low velocity associated with materials that have lost their resistance due to the increase in pore pressure (Vs $<$ 100 m/s) and the areas where eventually more landslides will occur (120 $<$ Vs $<$ 200 m/s) if mitigation work is not carried out. The most stable zones correspond to materials with velocity values greater than 250 m/s that overlap a substratum at an average depth of 8 m. In the case of a high risk of landslide, when it is not advisable to perform active source experiments, ANT can provide good results to determine the extension of the sliding materials.

Keywords — P-wave refraction, seismic tomography, seismic interferometry, surface waves, bedrock

Introduction

Landslides are usually caused by subsurface materials saturation (or poor compaction). In addition, sudden landslides occur under a stress regime in which the land mass is affected by extraordinary precipitation or the induced stress caused by an earthquake (Jongmans and Garambois, 2007). Seismic methods for subsurface characterization include seismic refraction and spectral analysis of surface waves (whether from an active or passive source) to obtain, more accurately, the bedrock irregularity (Harba et al., 2019). However, to cover large areas or acquire data in topographically complicated terrain, the results are only a sample of the magnitude of the problem in the case of landslides.

ANT has become popular in the last decade to characterize the subsoil structure. The principle of the method is based on Seismic Interferometry (SI), the cross-correlation of recorded seismic noise to extract the so-called Empirical Green Function (EGF). A summary of historical background and various applications in science and engineering at different scales are described by (Larose et al., 2015) and (Schuster, 2016). For example, in the case of landslides, SI has been used to identify the extent of the elastic properties contrast between the soft materials and the bedrock (Renalier et al., 2010; Pilz et al., 2014; Harba et al., 2019; Chávez-García et al., 2021). Additionally, the coda of the EGFs has allowed monitoring to detect velocity changes before the potential mass motions (Mainsant et al., 2012; Del Gaudio et al., 2013; Le Breton et al., 2021).

Mexico City is a densely populated city. Its western side is topographically abrupt, and the geological risk is increased because the subsoil structure is composed of silt-sandy materials interspersed with clasts and tuffs, originated by pyroclastic-detritus flows and ash deposits susceptible to landslides. A small ecological-sustainable park is at risk of disappearing in that area due to landslides caused by underground runoff and leaks in drainage systems. The park is located on the bank of a piedmont that was reforested, bordered by a river, and a residential area where vegetable planting is carried out and the habitants use it as a recreational area (Figure 1). This work aims to determine the lateral extent of materials prone to landslides by analyzing velocity images obtained from surface waves produced by seismic refraction and ambient seismic noise.

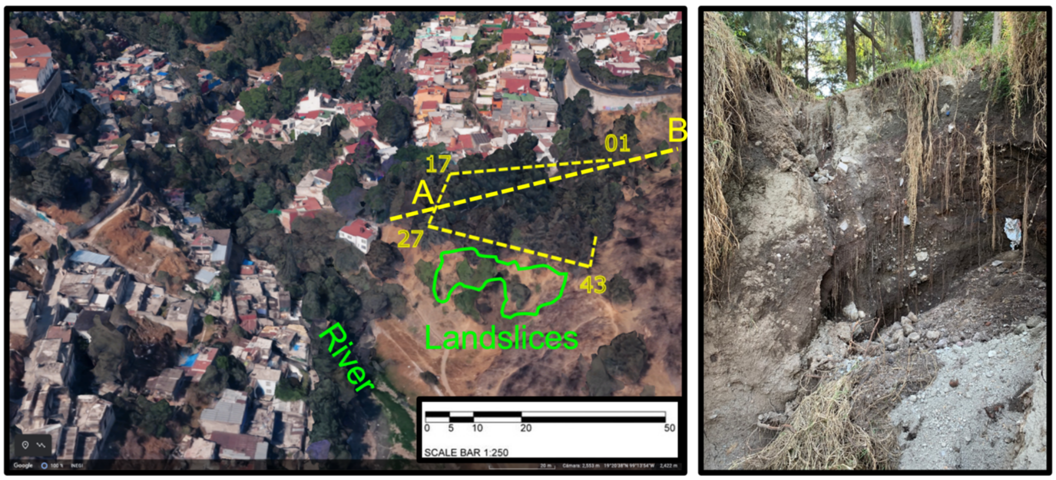

Figure 1: Images of the site study (left) and an example of a landslide (right). The dashed yellow lines indicate a refraction profile (AB) and a seismic array at whose vertices the geophone number is indicated.

Method

We use linear and semi-enclosed arrays of 48-4.5 Hz vertical geophones separated every 5 and 2.5 m to conduct active source and ambient noise seismic acquisitions (Figure 1). From active seismic source records, 24 sources using a sledgehammer, we produce in-depth images of P wave velocity (Vp) and S wave apparent velocity (Vs) using seismic refraction and spectral analysis of surface waves (SW) methods, respectively. A first approximation of Vp distribution (using the linear array) was obtained using the seismic refraction method. Subsequently, the area inside the semi-enclosed array was discretized with cells proportional to receiver separation. Then, the refracted time arrivals at each cell were linearly adjusted to obtain the slope inverse (Vp) and the intercept time to estimate the bedrock depth (Cárdenas-Soto et al., 2022).

In the case of Vs, we calculate dispersion curves (Herrmann, 2013) of all refraction records with a source-receiver distance greater than 15 m, and we use the group velocity times to elaborate tomographies in the frequency range of 6 to 24 Hz using the open-source libraries of (Rücker et al., 2017). Similarly, ANT images were calculated in the same frequency range. To do this, we normalize the records by 1-bit and spectral whitening (Bensen et al., 2007) and conduct cross-correlations between all pairs of receivers in 8s time windows over 30 min to obtain the so-called EGFs (Shapiro and Campillo, 2004). Subsequently, we stack acausal and causal parts of these functions and get group velocity dispersion curves.

Results

Figure 2 shows a SRT of the linear array on the apparently most stable side of the park. Deposits of soft materials are observed at the lower part of the slope with Vp values less than 600 m/s (typical velocities of weathered materials). The line extension allows defining a second layer with an irregular structure with poorly consolidated materials (Vp=800 m/s). Vp values greater than 1200 m/s can be associated with the bedrock at depths greater than 10 m. The materials susceptible to sliding correspond to a filling deposit, which is highly saturated.

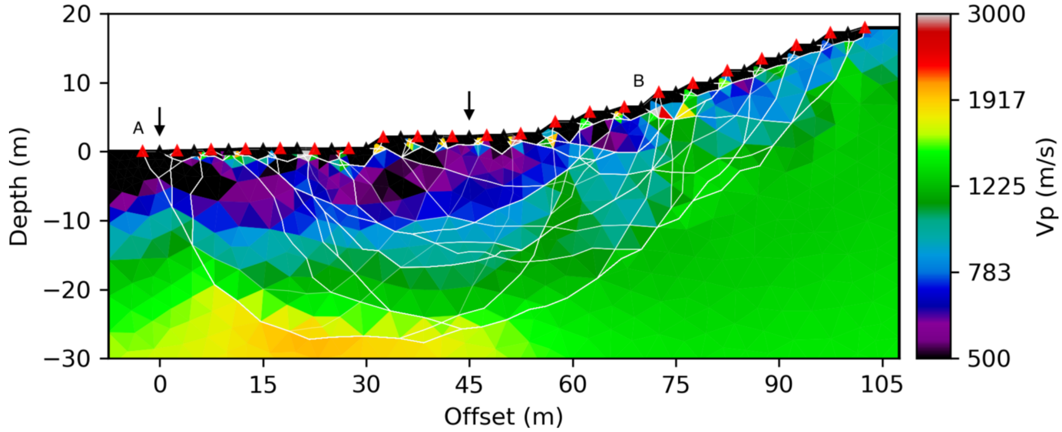

Figure 2: SRT of the linear array. Red and black triangles represent the position of the sources and geophones, respectively. Black arrows point out the crossing with the semi-enclosed array. The figure was produced by the open-source libraries of (Rücker et al., 2017).

One way to cover a more significant area extension is by seismic tomography. We took advantage of the semi-enclosed array in the study area to create a Vp tomography of refracted arrivals and another of Vs using dispersion curves, both active source tomographies. Figure 3a shows the selection of the first arrivals of all refraction records using. Direct arrivals show that Vp in the first layer is approximately 400 m/s. Refracted arrivals (after a critical distance of 20 m) exhibit large dispersion, indicating the bedrock is irregular with a Vp average of 1200 m/s according to the values in Figure 2. Figure 3b shows the velocities representation of the discretized model. The bedrock average depth is 8 m. A higher velocity zone is observed in the northern part of the array, between 8 and 10 m depth with Vp reaching up to 3000 m/s.

Tomography images derived from dispersion curves of the SASW and those extracted from EGFs are shown in Figure 4. The images correspond to an average frequency of 24 Hz, whose vertical wavelength is proportional to the first 3 m depth (with Vs average of 300 m/s). Both images show velocity zones less than 200 m/s. However, Vs values less than 100 m/s are obtained by ANT, whose lateral extension indicates the areas of softer or highly saturated materials and prone to slip between geophones 24 and 42 (according to direct observations in the eastern part of the array). Velocity values greater than 300 m/s, which correspond to compact materials, are observed at the array center. The velocity structure described by these values is similar in both methods in the southern part of the array but differs in position in the northern part. Differences in velocity values distribution are due to the nature of surface waves and the coverage lack in the northern part of the array. Furthermore, ambient noise tomographies for frequencies below 24 Hz (not shown here for brevity) corroborate the existence of such anomaly at greater depth.

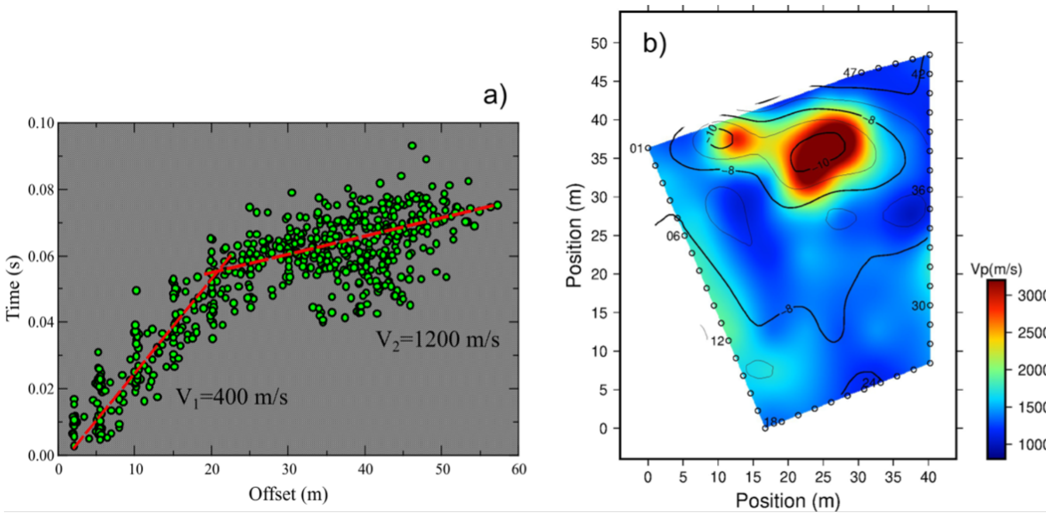

Figure 3: a) First arrival travel times (green circles) at all receivers due to all sources. Vp velocities of the first and second layer are indicated. b) Vp tomography obtained from sources and receptors at the surface. Open black circles indicate the geophones position.

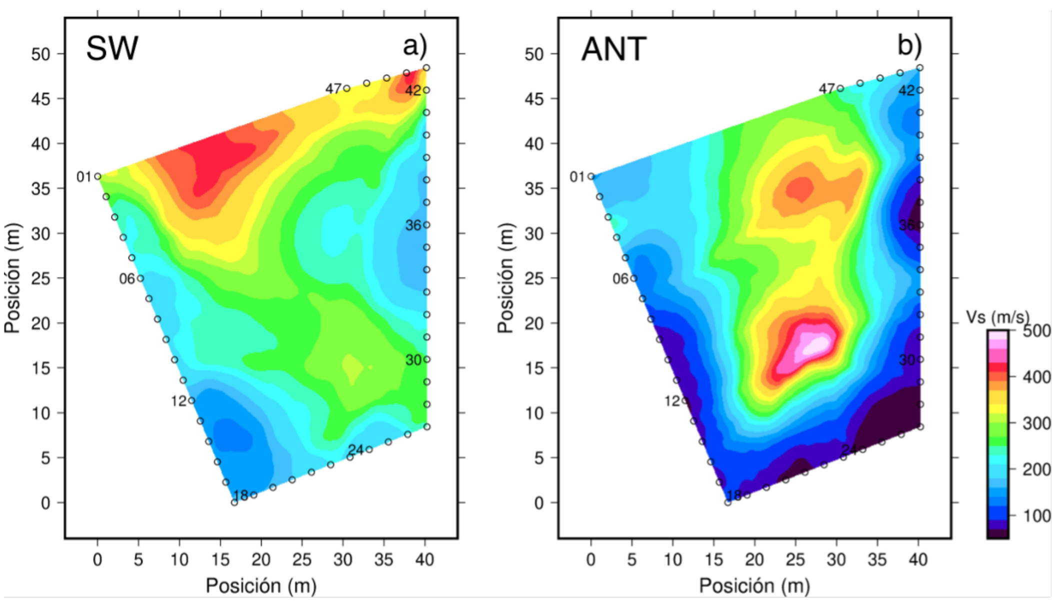

Figure 4: Vs tomographies built from dispersion curves at an average frequency of 24 Hz. a) Velocities obtained from surface waves of active source. b) Velocities obtained from surface waves of seismic noise. Open black circles indicate the geophones position.

Conclusions

A quadrangular seismic array allows exploring the subsoil structure using seismic refraction and seismic interferometry methods. We apply these methods to obtain velocity distribution images (Vp and Vs) of materials prone to landslides. The refraction method helps determine the bedrock depth, which can also be inferred into the array by taking advantage of surface sources and receiver geometry. At the study site, the surface waves generated from an active source and extracted from the ambient noise allowed to delineate the extent of materials close to sliding, whose Vs values are less than 200 m/s and notably contrast with the area of more compact materials.

We find the best Vs velocities correlation obtained from both methods is observed on an average frequency of 24 Hz. Future research will analyze the differences due to the surface waves character and produce a 3D-Vs model. We can point out that in the case of a high risk of landslide, when it is not advisable to induce stress into the subsoil, ambient seismic noise can provide practical results to determine the extension of the sliding materials.

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