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Local Seismic Response Analysis in the Large Büyükçekmece (Turkey) Landslide Area by Detailed Engineering-Geological and Numerical Modelling

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ABSTRACT

The Büyükçekmece landslide area is located in the eastern part of Avcilar peninsula (Turkey - Istanbul). The landslide (about 1500 m wide and 2200 m long) involves upper Oligocene to lower Miocene deposits, consisting of silty clays, tuffs and sands. A detailed engineering-geological model of the landslide slope was reconstructed to analyze the local seismic response of the landslide mass and assess possible conditions for the re-activation of the landslide under earthquake shaking . Seismic refraction, geoelectrical and geophysical investigations, single-point noise measurements and noise arrays were performed so far to define the landslide mass geometry and to attribute mechanical properties to the involved soils. The obtained results demonstrate that the local seismic response of the landslide slope is not negligible and it is strictly related to the geological setting as well as to the properties of the landslide mass. A preliminary numerical modelling was carried out along one longitudinal section of the landslide through the finite difference code FLAC 7.0. The numerical modelling demonstrated a strict relation between the geological setting of the landslide slope and the local seismic response, indicating that the interaction between seismic waves and landslide mass cannot be neglected to assess re-future activations of the landslide.

Introduction

Earthquake-induced landslide reactivation represents a big concern in seismic risk management since severe damage and losses were recently caused by co-seismic slope failures. In this regard, the last seven years recordings demonstrated that more than 50% of the total losses due to landslides worldwide are attributed to co-seismic slope failures (Petley, 2012). Moreover, as reported by Bird and Bommer (2004) the greatest damage caused by earthquakes is often related to landslides. This was the case for the Las Colinas landslide, triggered by the Mw 7.6 El Salvador earthquake of January 13th , 2001, which caused about 585 deaths.

A great effort is required to evaluate changes in the stability conditions of slopes under seismic shaking as well as to quantify their co-seismic or post-seismic mobility in terms of expected displacements. The behavior of slopes depends on complex interactions between seismic waves and existing landslide mass; in particular, it is controlled by several features among which the slope geometry, the landslide mass properties and the physical characteristics of the seismic

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waves (Lenti and Martino, 2013). Such interactions can be solved by stress-strain numerical modeling, performed under dynamic conditions. Nonetheless, to carry out these modeling very strong constraints are requested to reproduce the geological setting of the slope and to output reliable amplification functions. A fundamental contribution is provided by high-resolution engineering-geological reconstructions as well as by seismic measurements on site.

In the frame of the European Project "MARSite – Marmara Supersite: new directions in seismic hazard assessment through focused Earth observation in the Marmara Supersite" a case study was selected 35 km East from Istanbul, in the Avcilar-Beylikdüzü peninsula, about 15 km North from the seismogenetic North Anatolian Fault. This area is of particular interest for landslide susceptibility to earthquake triggering as: i) it was recently struck by the 17th August 1999 Mw 7.4 Kocaeli and by the 12th November Mw 7.2 Düzce earthquakes; ii) several rototranslational landslides were recognized; these landslide have width ranging from 250 up to 1000 m, length varying between 300 and 1850 m and maximum depth of sliding surface ranging from some tens of meters up to 100 m. The landslide volumes vary from 1 Mm^3 up to 100 Mm^3. Most of these landslides are located along the costal slopes. The largest one is located in the Büyükçecmece area where it widely involves buildings and roads; therefore, this landslide was selected as pilot-site in the MARSite project framework, to study the interactions between seismic waves and existing landslide masses.

Geological Setting

The geological setting of the Büyükçekmece landslide area was defined according to previous studies (Dalgiç, 2004; Duman et al. 2006). In the Avcilar-Beylikdüzü peninsula the Paleozoic basement is composed of Devonian limestones belonging to the Trakya and to the Dolayoba Formations which are overlaid by Oligocene to upper Miocene sedimentary rocks (Figs.1, 2).
These deposits can be divided into the following units: the Danisment Formation (upper Oligocene) consisting of stiff clays and claystone-shales containing loose sand horizons and tuff levels of different thicknesses (Fig.1a,b); the Kiraç member of the Istanbul Formation (upper Oligocene - lower Miocene) consisting of sands and gravels belonging to fluvial deposits generally poorly or not cemented (Fig.1c) with rare interbeds of tuff; the Bakirköy member of the Çekmece Formation (upper Miocene) consisting of alternating calcarenites, marls and clay layers (Fig.1d).

Manmade fills with average thicknesses of about 2 m widely cover the sedimentary deposits due to the intense and recent urbanization of the area. According to Sen (2007), the structural setting of the Avcilar-Beylikdüzü peninsula is characterized by two fault systems. The first one is NW-SE oriented and dislodges the Danisment Formation; the age of the fault system is probably pre-Upper Miocene as it does not cut the Upper Miocene deposits. The second fault system is NNW-SSE to WNW-ESE oriented and cuts the deposits of the Çekmece Formation. These faults are considered as extensions of the North Anatolian Fault (Gökasan et al. 2002) and the recorded microseismic activity suggests that they are still active because seismicity is polarized according to tectonic stress field (Örgülü, 2011).

Geomorphological evidence of pre-existing landslides were also collected through satellite images as well as field surveys in the Büyükçekmece area (Fig.2). Based on these evidences

characteristic landforms of a rototranslational landslide were recognized and mapped: they include a main scarp, several secondary scarps, several landslide terraces (these last ones are characterized by an evident counter slope and some of them are responsible for the presence of water pools), evidences of two earth flows, the first one located along the left side of the landslide mass and the second one at its toe (these earth flows are clearly visible in the field due to the presence of detachment and transportation zones).

Several evidences of damage to roads, buildings, walls, and infrastructures were also collected and taken into account to contour the landslide mass.

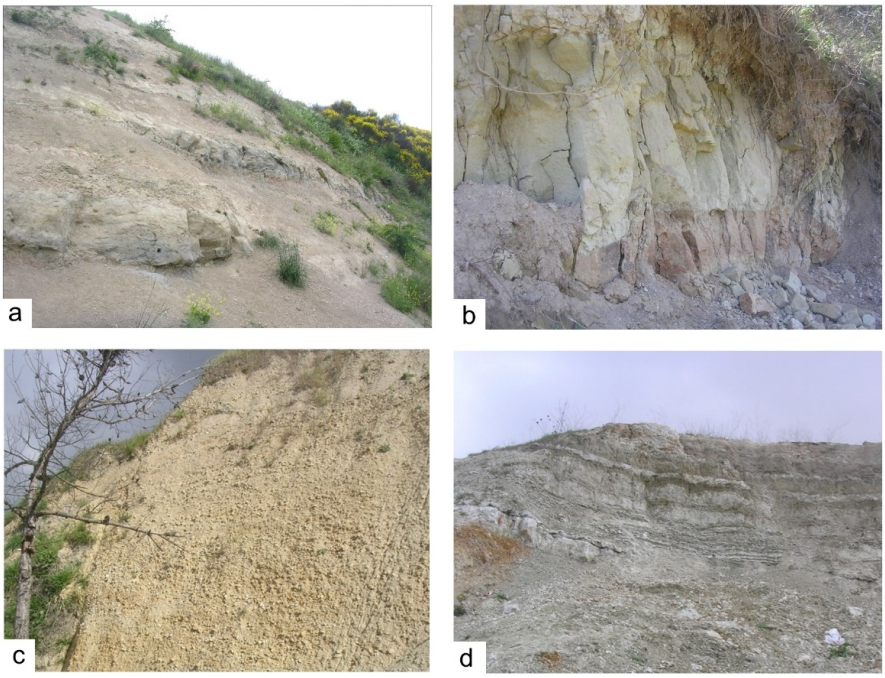


Figure 1. Geological units outcropping in the landslide area: a) claystones of the Danisment Formation (upper Oligocene); b) silty-clay with tuff levels in the Danisment Formation (upper Oligocene); c) sands and gravels belonging to the Kiraç member of the Istanbul Formation (Upper Oligocene – Lower Miocene); d) calcarenites and marls belonging to the Bakirköy member of the Çekmece Formation (upper Miocene).

Geophysical investigations

From the end of May 2014 until December 2014 geophysical investigations were carried out. These activities consisted in: 4 resistivity measurements; 32 seismic noise measurements; 27 P-wave refraction profiles, Multichannel Analysis of Surface Waves (MASW) and Refraction Microtremor (ReMi) profiles. The location of the geophysical investigations is reported in Fig.2.

Seismic measurements

The P-wave refraction measurements were performed along 69 m long lines and a hammer with a weight of 5 kg was used as source. In the analysis of seismic refraction data, it was possible to

reconstruct the subsurface geology up to 20 m. In the uppermost layer (up to 5 m below the ground level) P-wave velocities are very low, in the order of 300-400 m/s, but they locally sharply increase probably depending on the location of the water table. Regarding S-wave velocity profiles, derived from MASW and ReMi measurements, the penetration depth for MASW measurements is about 30 m, while it reaches about 80 m for the REMI measurements. Although a sharp velocity increase could be expected below the landslide mass, no such obvious impedance contrast was obtained; instead an almost gradual increase of velocity up to 600 m/s with depth was observed and a minimum superficial value of about 150 m/s was calculated.

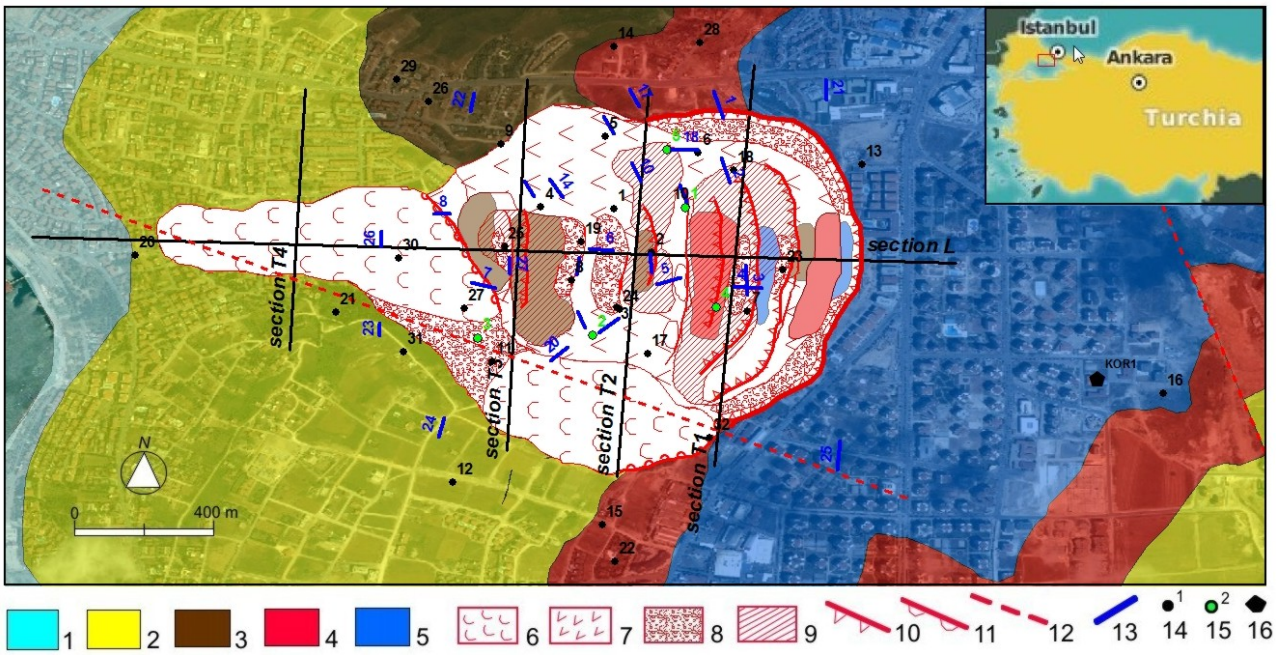


Figure 2. Geological map of the Büyükçekmece landslide area: 1) alluvial and coastal deposits (Holocene); 2) silty-clays of the Danisment Formation (upper Oligocene); 3) clays with tuffs for the Danisment Formation (upper Oligocene- lower Miocene); 4) sands and gravels of the Istanbul Formation - Kiraç member (upper Oligocene- lower Miocene); 5) calcarenites of the Çekmece Formation - Bakirköy member (upper Miocene); 6) earthflow debris; 7) rototranslational landslide mass; 8) slope debris; 9) landslide counterslope tilted terrace; 10) rototranslational landslide scarp; 11) earthflow crown; 12) fault; 13) seismic lines; 14) noise measurement station; 15) VES measurement point; 16) accelerometric station.

Seismic noise measurements were performed at 32 sites using GURALP CMG-6T velocimeter sensors with a natural frequency of 1Hz, using 50 min long time-windows. Data were processed using the horizontal to vertical specral ratios (HVSR) technique to derive the resonance frequencies. Results show that only few stations show clear resonance peaks generally close to 1Hz and within a wider range from 4 to 6 Hz.

The performed noise measurements pointed out anthropic vibrations (focused at about 1.5Hz) that could alter data interpretation as they interfere with the natural resonance . The identification of these anthropic vibrations relies on: i) sharp peaks visible on noise spectra: ii) semi-diurnal variations on a night and day regime, iii) correlation of the signal on the three components.

Nevertheless, such anthropic vibrations do not appear to be polarized along a given direction. Neglecting the anthropic peaks in the HVSR analysis, the obtained curves show that the landslide area is characterised by higher resonance frequencies (generaly >2Hz) than the sites located outside from the landslide (Fig.7a).

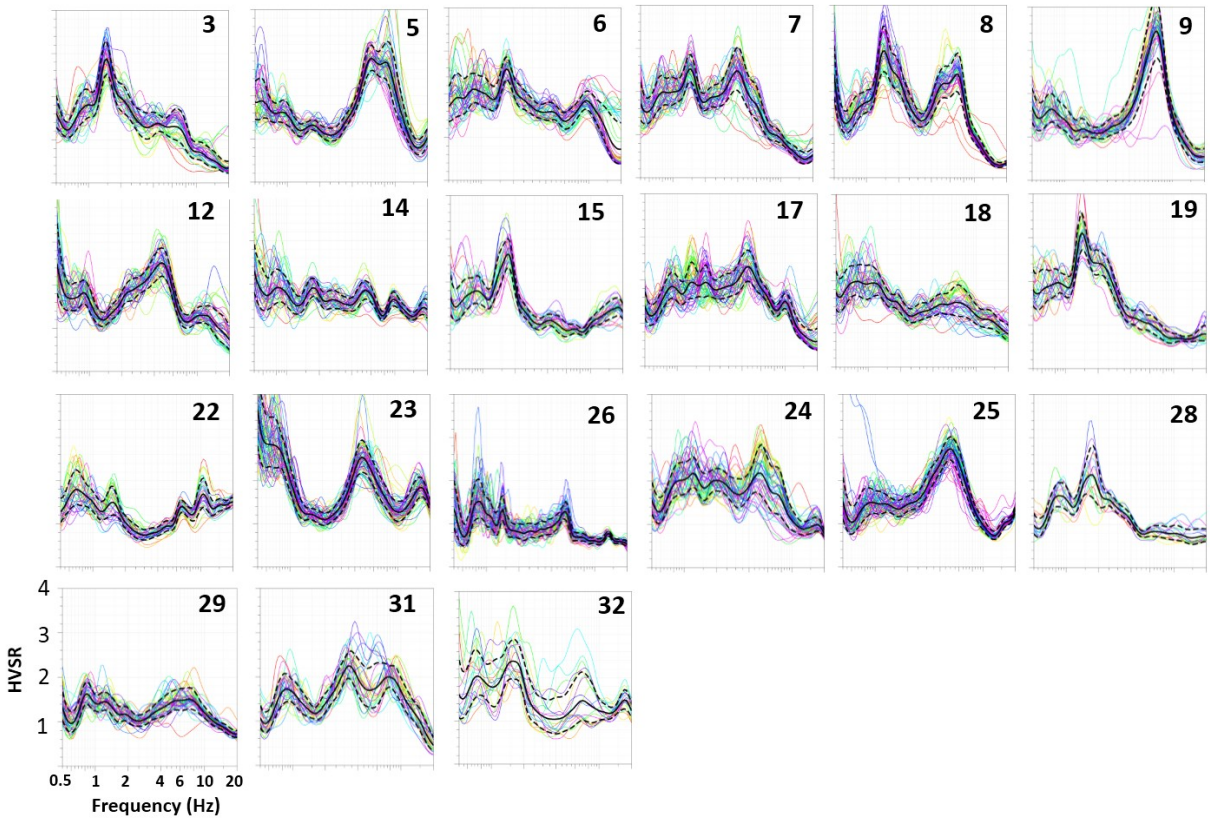
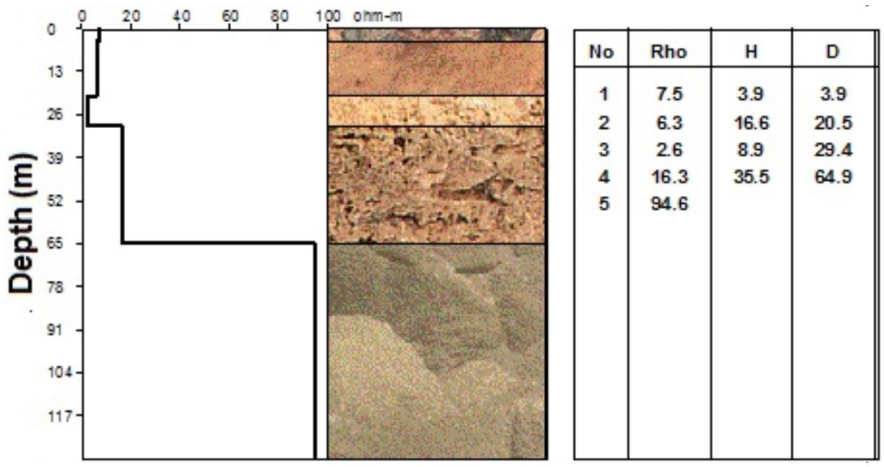


Figure 3. Some of the HVSR curves derived from the noise measurements performed in the Büyükçekmece landslide area (see Fig.2 for location).

Geoelectrical measurements

Resistivity measurements (vertical electrical sounding - VES) were performed at 4 points (see Fig.2 for location).The resistivity values measured within the landslide mass are generally lower than 20 ohm·m, i.e. a typical value for remoulded clayey debris. In the VES 3 profile (Fig. 3) there is a sharp increase of the resistivity up to 100 ohm·m at almost 65 m below the ground level that can be related to the sliding surface. The lowest resistivity values (of almost 10 ohm·m) can be related to the sandy deposits belonging to the Kiraç member of the Istanbul Formation.



No	Rho	H	D
1	7.5	3.9	3.9
2	6.3	16.6	20.5
3	2.6	8.9	29.4
4	16.3	35.5	64.9
5	94.6		

Figure 4. Resistivity values and related subsoil model from the VES 3 profile (see Fig.2 for location).

Engineering geological model

The geophysical measurements and the geological setting of the landslide slope were combined to obtain a high-resolution engineering-geological model that distinguish several lithological units, characterized by specific mechanical properties.

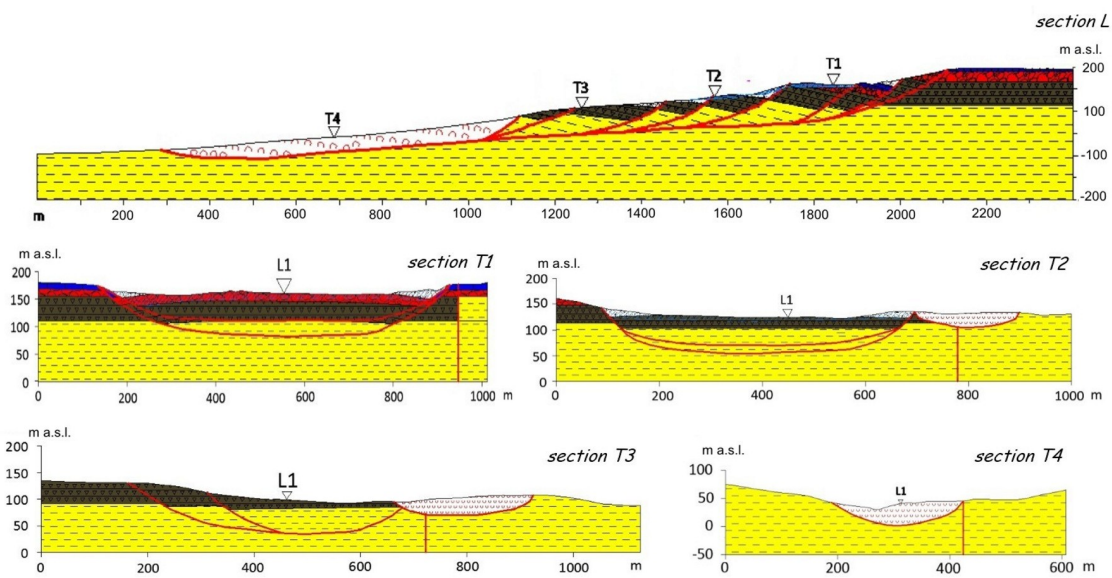


Figure 5. Geological cross-sections constructed along the traces L, T1, T2, T3 and T4 of Fig.2. See Fig.2 for the legend.

Based on the collected geological and geomorphological evidences as well as on the geophysical investigations performed in the framework of the MARsite project, 5 geological cross-sections were reconstructed in the landslide mass area (1 longitudinal cross section L and 4 transversal cross sections T1, T2, T3 and T4). To this aim:

- the seismic refraction lines and the MASW were considered to establish variations of Vs (i.e. dynamic stiffness) with depth and to project the so derived seismo-stratigraphic logs along the geological cross sections;
- the noise measurements were considered to check the consistency of the geological layering with possible resonance frequencies;
- the VES resistivity logs were projected along the geological cross sections to compare the resistivity values with the subsoil layering;
- boreholes stratigraphic logs were considered.

Numerical modelling of the local seismic response

To assess the local seismic response of the landslide and possible relations with the geological setting of the slope and its topography, 2D numerical simulations in viscoelastic conditions were performed on section L with the finite difference code FLAC 7.0 (Itasca, 2011). The section was discretized into quadrilateral zones whose sizes allow an accurate representation of wave transmission through the model up to 15 Hz. Absorbing quiet boundaries and free field conditions were applied along bottom and lateral boundaries to prevent the reflection of outward propagating waves. Energy dissipation in the soil was solved by a Rayleigh damping function. A first order Ricker wavelet, with a frequency content ranging from 0.1 to 15 Hz, was applied in the form of a vertically upward propagating SV stress wave. The numerically derived seismic amplification function for section L is shown in Figure 6. It represents the spectral velocity ratios between the superficial receivers located along the topographic surface and the outcropping bedrock. This amplification function is very complex and strongly controlled by the geological setting of the slope. No significant amplification is observed outside from the landslide area while relevant amplifications (3.1) are observed in the landslide mass at frequencies between 2 and 4 Hz, that can be related to the impedance contrast between the landslide mass debris and the local substratum (i.e. seismic bedrock).High-frequency amplifications resulted on the edges of the tilted landslide blocks.

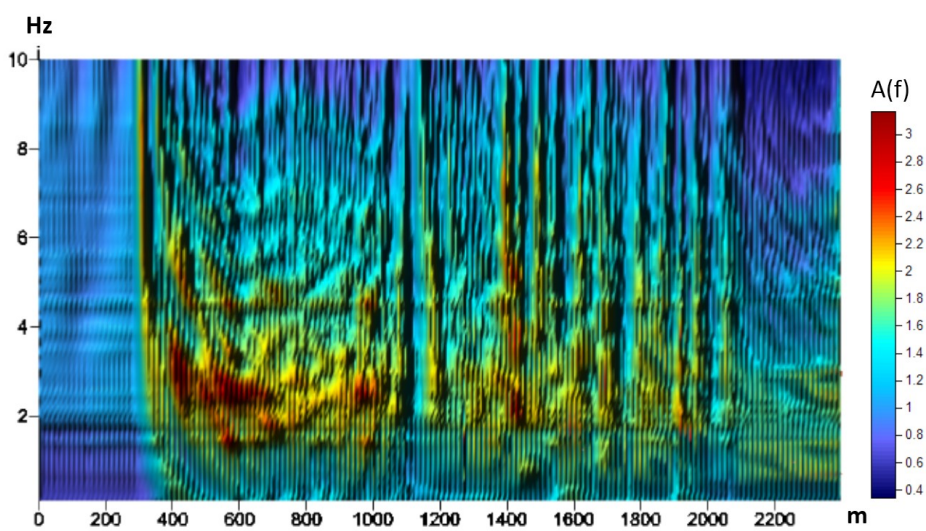


Figure 6. Amplification function obtained from FLAC modeling along the section L of Fig.2.

A comparison between the numerical transfer function obtained around station 8 of Fig. 2 and the corresponding HVSR is reported on Fig. 7d-e: it shows a general agreement in the frequency range 3-5 Hz, while the numerical amplifications at lower frequencies can not be compared with the experimental data because of the presence of the aforementioned anthropic vibrations at about 1.5Hz.

Conclusion

The study of the Büyükçecmece landslide led to a a high-resolution engineering-geological model based on field evidences and geophysical investigations. High variations of geological and mechanical properties in the landslide slope, were also derived though specifically performed laboratory tests. The complex geological setting is responsible for a local seismic response characterized by a wide range of amplified frequencies; nonetheless, the landslide area is characterised by higher resonance frequencies (generaly >2Hz) than outside sites. Numerical analyses will be carried out in future to highlight the interaction between seismic waves and landslide mass to provide possible scenarios of earthquake-induced landslides reactivations. . Moreover, a multisensors monitoring system, installed a few months ago in the framework of the MARSite project, is expected to provide ground-motion recordings as well as data on induced landslide movements and water pressure changes to further constrain numerical modeling.

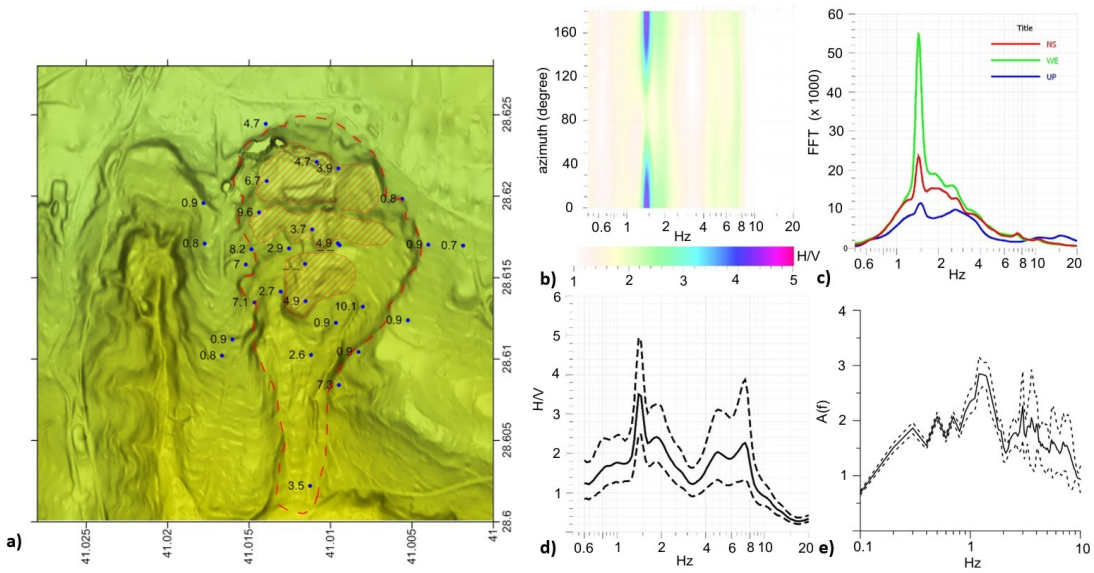


Figure 7. a) Distribution of resonance frequencies in the landslide area. Noise measurements at station 8 (see Fig.2 for location): b) H/V vs. azimuth; c) 3-components FFT; d) H/V spectral ratios; e) amplification function from FLAC modeling around station 8 along section L.

Acknowledgments

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