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Application of Refraction Microtremor (ReMi) technique for determination of 1-D shear wave velocity in a landslide area

S. Coccia [a], V. Del Gaudio [a,*], N. Venisti [b], J. Wasowski [c]

[a] *Dipartimento di Geologia e Geofisica, Università degli Studi di Bari, via E. Orabona, 4, 70125 Bari, Italy*
[b] *Osservatorio Sismologico, Università degli Studi di Bari, Italy*
[c] *Istituto di Ricerca per la Protezione Idrogeologica, Consiglio Nazionale delle Ricerche, Bari, Italy*

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ABSTRACT

The application of the Refraction Microtremor (ReMi) method on slopes affected by or prone to landsliding is complicated by the presence of lateral lithological heterogeneities and irregular topography, which may hinder the extension of the geophone array to the minimum lengths (100–200 m) usually adopted in standard applications of this technique. We focus on deriving one-dimensional shear-wave velocity (Vs) vertical profiles from the analysis of microtremor recordings carried out in the municipality of Caramanico Terme (central Italy) where the seismic response has been monitored with a local accelerometer network since 2002. The stability of the ReMi data acquisitions and the reliability of the results in irregular landslide terrain were tested by using ReMi campaigns in three different periods and different acquisition parameters (seismograph channel number, geophone frequency and spacing). We also investigated the possible presence of directional variations in soil properties by carrying out noise recordings along L-shaped arrays. The influence of changing environmental conditions and of different acquisition parameters was tested by comparing the data obtained from different campaigns, using the same acquisition parameters, with the data from simultaneous acquisitions using different parameters. The tests showed that stable results can be obtained under different acquisition conditions provided that i) the ratio between the coherent and incoherent part of ambient noise is sufficiently high and ii) spatial aliasing does not contaminate the signal in the p (slowness)–f (frequency) matrix near the picking area: the latter condition can be satisfied by selecting geophone frequency and spacing appropriate for the site characteristics and for the investigation purpose. The differences in Vs measured in two orthogonal directions did not exceed 10–20 % and their analysis suggests that these directional variations are most likely due to anisotropy in noise source distribution rather than in material properties.

The Rayleigh wave velocity dispersion curves obtained from microseimic noise recordings were then inverted with the DINVER software package to derive vertical distribution of the Vs. We reconstructed vertical profiles of Vs through the joint inversion of fundamental and higher modes, constrained by borehole information. The results from a site of a recent deep-seated slope failure showed that both colluvium few tens of meters thick, and the underlying mudstone have lower velocities than those of the same formations present in the surrounding area not involved in mass movements. This suggests that the mudstone has been affected by slope deformations at this site.

1. Introduction

Considerable amount of earthquake damage in hilly and mountainous areas is caused by slope failures triggered by seismic shaking (Keefer, 1984). However our understanding of seismic slope response is still limited because of the scarcity of ground motion recordings on landslide-prone slopes. Furthermore, numerical modelling of slope behaviour under earthquake shaking is not easy because the acquisition of relevant geotechnical parameters of slope materials is difficult in sites characterised by rough topography and sharp lateral lithological and/or physical heterogeneities. The assessment of subsurface geology through borehole or "active" geophysical surveying is expensive and is typically limited to post-factum (post-failure) local scale investigations. In this context it is of interest to explore the capability of recently developed cheaper and quicker "passive" geophysical techniques that exploit natural signal sources, like the Refraction Microtremor analysis technique (ReMi) (Louie, 2001), also known as "Noise Analysis of Surface Waves" (NASW). This methods is based on ambient noise measurements that are carried out with seismic arrays to obtain information on surface wave velocity dispersion.

* Corresponding author. Tel.: +39 080 5442279; fax: +39 080 5442625.
E-mail address: delga@geo.uniba.it (V. Del Gaudio).

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The inversion of dispersion curves can provide a one-dimensional shear wave velocity (Vs) model down to a depth related to the length of the array, and thereby furnish useful data for the numerical modelling of seismic site response (Havenith et al., 2007). On the other hand, uncertainties affecting inversion results pose some problems to a complete stand-alone application (Dal Moro et al., 2006). Therefore, within a research aimed at improving the understanding of factors controlling seismically induced landsliding, we tested the effectiveness of ReMi in providing parameters relevant for the assessment of seismic response of landslide-prone slopes.

We applied this method in the municipality of Caramanico Terme (Central Italy), an area often subjected to mass movements caused by earthquakes and meteorological events (Wasowski and Del Gaudio, 2000). In this area an accelerometric monitoring has been conducted since 2002 to study seismic response of unstable slopes. Strong motion data are being acquired through a specifically designed local accelerometric network composed of 5 stations sited in different lithostratigraphic and topographic settings. The results of the accelerometric monitoring provided evidence of amplifications on a landslide that in 1989 mobilized 30–40 m thick Quaternary colluvial deposits overlying Pliocene mudstones (Del Gaudio and Wasowski, 2007).

ReMi data for an analysis of seismic slope response, and specifically to determine Vs vertical profiles, were acquired at sites near the accelerometric stations both within and around the landslide. On hillslopes affected by landslides considerable difficulties can arise from local field conditions that often limit the extension of geophone linear spread below the lengths (100–200 m) commonly adopted in ReMi standard practise. Moreover, the distance from anthropic sources of microtremors can cause unfavourable noise conditions in comparison to other well established cases of application.

Here we first describe several tests conducted to assess the repeatability of data acquisition and the uncertainty of the estimated Rayleigh wave dispersion curves in case of a landslide-prone slope. The assessment relies on comparisons of the data acquired by conducting ReMi campaigns in three different periods. Then we illustrate how vertical distributions of Vs were determined from Rayleigh wave dispersion curves inverted with the software package DINVER (Wathelet, 2005), which provided a set of models compatible with the observed dispersion curves within the data uncertainty limits. Finally, we discuss the implications of the data inversion results for a hillslope affected by a recent deep-seated landslide.

2. Description of the study area

The town of Caramanico Terme is located in a seismically active part of the Apennine chain, in a fault-bounded valley (Fig. 1). The complex geological setting and the unfavourable hydrogeological conditions that characterise the area around the town determine a diffuse presence of marginally stable slopes with a long record of historical landsliding, typical of mountainous settings subjected to relatively high average precipitation and seismic activity. High local relief, steep slopes, gully erosion, and strong river down cutting are the main geomorphologic factors predisposing the recurrence of mass movements (Wasowski and Del Gaudio, 2000).

The main lithologic units of the Caramanico area are (Fig. 1): 1) Miocene age limestones; 2) evaporitic succession (Messinian); 2) marly mudstones of Early Pliocene age, which form the substratum that crops out along the slopes of the Orta River Valley; 3) carbonate megabreccias (Quaternary?), which form the caprock of the Caramanico hillslopes; 4) soils (colluvial materials, landslide deposits, waterlaid and eluvial sediments, artificial ground - Holocene). The presence of these different lithologies, with their lateral and vertical changes, results in a hydrogeologic setting with high permeability contrasts and complex groundwater flow patterns.

A majority of recent damaging slope failures have been linked to long periods of precipitation and typically involved remobilisations of older landslides. The 1989 landslide is a typical example of reactivation of pre-existing mass movements and was triggered by two major storms that occurred during a 15 day span (Wasowski, 1998). This movement, mobilized about 40 m thick colluvium overlying Pliocene mudstones and locally affected the thick accumulations of carbonate debris.

In addition, several historical records describe landslides and ground deformations induced by earthquakes in the Caramanico area (Wasowski and Del Gaudio, 2000). For example a large mass movement was caused by an earthquake of 1627 (estimated magnitude between 6.7 and 7.0), with epicentre located in northern Apulia, about 100 km from Caramanico.

Seismic response of marginally stable peri-urban slopes at Caramanico Terme is currently investigated with the aid of a permanent network of 5 accelerometric stations. The monitored sites are characterised by different topographic and lithostratigraphic conditions (Fig. 1): (1) CAR1, sited on Pliocene mudstones, within a slope dipping 18° to WSW ; (2) CAR2, 600 m to SSE of CAR1, within the same hillslope dipping 11° to WSW, but on the head of 1989 landslide; (3) CAR3, on the rim of an over 50 m deep gorge locally oriented WNW–ENE, on 10 m thick Messinian carbonate breccia overlying Miocene limestones; (4) CAR4 ("reference station"), 2.5 km SE of Caramanico, on the same Miocene limestones as in CAR3, forming a gentle slope (8°) dipping to NW; (5) CAR5, 200 m upslope CAR2, on the same thick colluvium as in CAR2, but not involved in landsliding, in a gently inclined (< 7°) area.

For two out of five monitored sites, the numerous recordings acquired since 2002 showed the presence of significant amplifications with pronounced maxima systematically oriented along an almost constant site-specific direction, regardless of the event source location. This direction appears related to local topography features and in one case (CAR2) coincides with the main direction of movement of a deep-seated landslide. These observations lead to suggest the presence of a directional resonance in the dynamic response of the two sites to seismic shaking, which has subsequently been confirmed by analyzing the directional variations of average horizontal to vertical spectral ratios (HVSR) calculated both for the recorded seismic events (Del Gaudio and Wasowski, 2007) and for microtremor recordings carried out using portable seismograph with velocimetric characteristics (Del Gaudio et al., 2008). The HVSR data also supported the hypothesis that the presence of a landslide body contributes to determine conditions of site response directivity, possibly caused by a concomitance of more factors (e.g. local topography, lateral changes of thickness, lithology and physical characteristics, anisotropy of landslide body material properties controlled by gravity driven movements). The influence of these factors could be investigated by modelling slope behaviour under dynamic conditions, but this requires additional data and one of the critical parameters for the numerical modelling is shear-wave velocity Vs.

In the following we report on the application of ReMi technique to obtain Vs down to typical depths of mass movements at Caramanico. This technique is based on the identification of Rayleigh wave trains in

Fig. 1. (a) Orthophoto of the study area showing lithological units and position of the five accelerometric stations: inset shows the geographical location of Caramanico Terme. Major landslides are indicated in green, geological contacts in light brown (after Wasowski and Del Gaudio, 2000). Explanation: Lm = Miocene limestones; Me = Messinian sandy-silty deposits with carbonate breccia; Mp = Pliocene mudstones; Bq = Quaternary limestone megabreccias; Sqh = Quaternary and Holocene soils (colluvium and artificial ground); red marks show the location of the accelerometric stations CAR1–CAR5; the labels 1989 and 1627 indicate the locations and years of occurrence of the landslides discussed in the text. (b) Geologic profiles of CAR1-5 sites (modified after Del Gaudio and Wasowski, 2007), drawn along the maximum slope directions; m a.s.l. stands for meters above sea level.