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Multiscale geophysical characterization of an unstable rock mass

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ABSTRACT

Hazard mitigation from rockfalls and landslides is a priority in densely populated areas. A proper characterization of the inner structure of the rock mass is key to the comprehension of the mechanisms enhancing the slope instabilities. To this aim multi-scale geophysical methods can provide a novel and valuable tool for a high-resolution imaging of the internal structure of the rock mass and unique constraints on the physical state of the medium. We present here a cross-hole seismic tomography survey coupled with laboratory ultrasonic velocity measurements and physical properties determination on rock samples to characterize the damaged and potentially unstable granitic cliff of Madonna del Sasso (NW Italy).

Results allowed to obtain: i) a lithological interpretation of the velocity field obtained at the site, ii) a systematic correlation of the measured velocities with physical properties (density and porosity) and macroscopic features of the granite (weathering and anisotropy) of the cliff. The multi-scale approach adopted within this study revealed to be crucial for the imaging at depth of the main fractures affecting the cliff (site-scale seismic tests) and for the understanding of the variations in the seismic velocity between altered and intact rock (laboratory-scale tests); similar approaches can be potentially used in further microseismic monitoring studies.

1. Introduction

Unstable rock masses can represent a serious threat to highly populated areas and can cause relevant damages. In order to effectively mitigate the hazard from rock mass instabilities, a detailed knowledge of the inner structure and of the physico-mechanical properties of the involved rock volume is required to forecast the localization of deformation and the pre-failure mechanisms (e.g. Willenberg et al., 2002).

The fracturing assessment, with particular reference to orientation, spacing, opening, filling and hydraulic properties of the discontinuities is key to determine geometry, location and orientation of potential sliding surfaces leading to rockfalls and landslides. Geological and geomechanical studies, remote sensing and aerial techniques can be used for this aim on the external surfaces of the studied medium. Geophysical methods are however the best approach to image the internal structure of the rock mass, undetectable with a comparable resolution by other techniques, thus providing valuable constraints on the physical state inside the medium. A review of the geophysical methods applied to the internal characterization of landslides and rockslides can be found in Bogoslovsky and Ogilvy (1977); Jongmans and Garambois (2007) and in Maurer et al. (2010). Successful results are documented from seismic methods, such as reflection, refraction, tomography and ambient noise measurements, electrical methods, such as electrical resistivity tomography (ERT) and spontaneous potential (SP), and electromagnetic methods, such as ground-penetrating radar (GPR).

Electrical methods provide important information about the water/fluid saturation, since electrical resistivity is strongly influenced by the water content and its conductivity, as well as the fracturing state (e.g. Méric et al., 2005; Lebourg et al., 2005); GPR can be useful to obtain a high-resolution imaging of fractures when the investigated rock mass allows a sufficient depth of penetration (e.g. Jeannin et al., 2006; Roch et al., 2006; Willenberg et al., 2008). However, among the available geophysical methods, seismic surveys are the only ones for which measurements are directly related to the mechanical properties of the rock mass (density and deformation moduli) and result more valuable for obtaining necessary mechanical data for the numerical simulation of the slope stability. Moreover, seismic data are also fundamental for the definition of a reliable velocity field to be used in microseismic monitoring applications.

Bruno and Marillier (2000) tested high-resolution seismic reflection surveys combined with other geophysical tests on a landslide in the Swiss Alps. Their methodology allowed the identification of the slip surface within a gypsum layer located at the depth of 50 m. Mauritsch et al. (2000) applied seismic refraction methods for the investigation of a large Alpine gravitative sliding in southern Austria, affecting slopes with a complex fabric given by limestones, dolomitic conglomerates, sandstones and shales. The variations in the P-wave velocity were interpreted as lithological changes and seismic data supported in the determination of the stable bedrock.

Over the last decades, geophysical tomographic imaging has considerably grown, leading to a 2-D or 3-D imaging of the analyzed medium,

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through inversion procedures. This technique was used by Jongmans et al. (2000) and Méric et al. (2005) showing a significant decrease in the P-wave velocity near the failure surface within the unstable mass.

Here we carried out a seismic cross-hole survey to characterize the unstable granitic cliff of Madonna del Sasso (NW Italy). During the survey, seismic sources were located both in well and at surface, as well as the receivers. The travel times of the first arrivals among different source-receiver separation were then used to produce a tomographic velocity cross-section of the subsurface between the two boreholes (Bregman et al., 1989; Lines and LaFehr, 1989; Chen et al., 1990; Jackson and McCann, 1997; Rao and Wang, 2005; Gu et al., 2006). Cross-hole tomography is a very suitable methodology for our purposes because it is expected to provide higher resolution imaging with respect to surface-based methods, since the energy does not travel through the highly attenuating near surface and the travel distances are shorter. In addition, the resolution of cross-hole tomography is not depth-limited since the majority of the energy travels between the wells so that a trans-illumination of the imaged medium can be achieved. This is even more important in a highly fractured medium, as the one object of the study, where waves travel along complex paths that could be hidden if only surface measurements are available.

Geophysical field data can be integrated by laboratory surveys to establish a link between rock properties and geophysical data. Heincke et al. (2006) applied 3-D seismic tomography to an unstable Alpine mountain slope, finding significantly lower apparent velocities in the field compared to the average ones determined from laboratory analyses of intact rocks collected at the investigated site. The gap has been interpreted as due to the widespread presence of dry cracks, fracture zones and faults at different scales.

Ultrasonic pulse velocity measurements have been widely applied on granite samples since the elastic-wave velocity is significantly affected by the volume, distribution and shape of rock pore space and it is well known that elastic wave velocities are substantially reduced in the presence of thin cracks (Benson et al., 2007; Hadley, 1976; Stanchits et al., 2006). Vasconcelos et al. (2008) carried out P-wave ultrasonic velocity measurements on granite specimens with different size and shape, presenting statistical correlations with physical (density, porosity) and mechanical properties (modulus of elasticity, compressive and tensile strength). Weathering and moisture were found to significantly affect the values of ultrasonic pulse velocity. Chaki et al. (2008) investigated the decrease in the ultrasonic pulse velocities versus increasing heat treatment temperature in granites, interpreted as an effect of micro-cracking due to thermal treatment, in agreement with the results obtained for other igneous rocks (Vinciguerra et al., 2005). Cerrillo et al. (2014) investigated the correlations between physico-mechanical properties of granite samples and new parameters related to Fast Fourier Transform (FFT) and attenuation, obtained from the ultrasonic evaluation, in addition to ultrasonic pulse velocity. These additional correlations strengthen the use of ultrasonic tests as a non-destructive useful method for granite physical and mechanical characterization.

Proper correlation of seismic velocities obtained at the field scale (1 to 100 Hz) with ultrasonic velocities at the laboratory scale (10 kHz to 1 MHz) has to be performed considering both the difference in the frequency range at which tests are executed and the investigated volume. Tested velocities are a measurement that integrates elastic properties over the scale corresponding to the wave length and therefore may provide different results in the different frequency ranges. Ciccotti and Mulargia (2004) showed that ultrasonic measurements in the kHz-to-MHz regime can determine about 10% overestimation of elastic moduli with respect to measurements carried out in the 0.01-to-20-Hz range. At low frequency, fluid pressure is equilibrated in pores and cracks, while at higher frequencies, the fluid has no time to flow and the fluid pressure is not equilibrated (O'Connel and Budiansky, 1976). This frequency-dependent behavior produces a dispersion which is experimentally observed in isotropic media and is generally called squirt-flow mechanism (Mavko and Nur, 1975; O'Connel and Budiansky, 1976; Thomsen, 1985). Dispersion is believed to drop off rapidly to less than 10% when effective pressure is increased (Zamora et al., 1994, and references therein), but this is strongly influenced by the density of cracks (Schubnel and Gueguen, 2003, and references therein) in the rock. Despite these limitations, ultrasonic measurements reliably approximate the seismic measurements performed on the field and are helpful for the lithological interpretation and the crosscheck of the field-scale measurements.

Therefore, laboratory ultrasonic measurements were also performed in this study to lithologically interpret the seismic tomography carried out at the field scale and for transferring the microscopic knowledge at rock sample level to the field scale rock mass. Rock samples were systematically collected at the site in order to take into account velocity differences deriving from the high level of variability and alteration within the unstable cliff. Other granite samples were also collected at the site for physical (density and porosity) and mechanical characterization (uniaxial compressive strength from Point Load test). Correlation between these laboratory parameters and the seismic velocity were then investigated. Results from different scales of study (field and laboratory) were finally compared with previous geological surveys (stratigraphic logs of continuous core drillings, geomechanical studies on the overall fracturing state) to provide a complete model of the studied rock mass.

2. Test site

The cliff of Madonna del Sasso (45°79′N, 8°37′E) is located in NW Italy, on the western shore of the Orta Lake (Fig. 1a). It is a massive granite outcrop bordered on three sides (N, E and S) by pseudo vertical walls, with a height of about 200 m (Fig. 1b). The actual steep and complex morphology derive from the intense mining activity lasting until a few decades ago, on the bottom of the cliff. At the top of the cliff a panoramic square lies at approximately 650 m a.s.l., in front of the XVIII-century sanctuary from which the place takes its name. At the bottom of the slope, between the cliff and the lake, there are several buildings, including houses and small factories, and a road (SP 46) connecting the towns on the western shore of the lake.

From a geological point of view, the area is totally characterized by a granitic rock mass, known as *Granito di Alzo*. This unit belongs to the non-metamorphosed, and generally low deformed, granitic masses, related to a late-Hercynian magmatic intrusion (lower Permian), that outcrops along the contact between the lithologies of the *Serie dei Laghi* and the *Ivrea-Verbano Zone* (Boriani et al., 1992; Giobbi Origoni et al., 1988). These granites, commonly known as *Graniti dei Laghi*, make a large batholith, elongated in NE–SW direction, which includes five large magmatic intrusions, among which the *Alzo-Roccapietra Pluton*, of granitic and granodioritic composition, outcropping between the lower Sesia Valley and the Orta Lake.

Since 1981 warnings related to movements and cracks opening observed at the panoramic square were reported by the local authorities. During the same year, 5 continuous core drillings were performed at the site and three of them (S1, S2 and S5) were equipped with a 30-meter-length aluminum casing for inclinometric monitoring. Inclinometric measurements were acquired two times per year until 1990, when a further episode of displacement damaged the borehole casings. Inclinometric recordings revealed moderate displacements, up to a maximum of 10 mm on the horizontal plane in 6 months (Regione Piemonte, 1993).

A geomechanical characterization of the site (Lancellotta et al., 1991) led to define the rock mass as intact or massive but affected by widely spaced discontinuities with good surface quality. Four main joint sets were identified (dip direction/dip): K1 (110/75), K2 (0/80), K3 (150/15) and K4 (50/75). These discontinuities (Fig. 2) tend to isolate two frontal portions of the cliff, which increase their instability depending upon the rock joints along the fractures and the foot edge.