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Characterization of the Vajont landslide (North-Eastern Italy) by means of reflection and surface wave seismics

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ABSTRACT

The mechanisms of the disastrous Vajont rockslide (North-Eastern Italy, October 9, 1963) have been studied in great detail over the past five decades. Nevertheless, the reconstruction of the rockslide dynamics still presents several uncertainties, including those related to the accurate estimation of the actual landslide mass. This work presents the results of a geophysical characterization of the Vajont landslide body in terms of material properties and buried geometry. Both aspects add new information to the existing dataset and will help a better understanding of the rockslide failure mechanisms and dynamics. In addition, some general considerations concerning the intricacies of landslide characterization can be drawn, with due attention to potential pitfalls. The employed techniques are: (i) high resolution P-wave reflection, (ii) high resolution SH-wave reflection, (iii) controlled source surface wave analysis. We adopted as a seismic source a vibrator both for P waves and SH waves, using vertical and horizontal geophones respectively. For the surface wave seismic survey we used a heavy drop-weight source and low frequency receivers. Despite the high noise level caused by the fractured conditions of the large rock body, a common situation in landslide studies, we managed to achieve a satisfying imaging quality of the landslide structure thanks to the large number of active channels, the short receiver interval and the test of appropriate seismic sources. The joint use of different seismic techniques help focus the investigation on the rock mass mechanical properties. Results are in good agreement with the available borehole data, the geological sections and the mechanical properties of the rockmass estimated by other studies. In general the proposed approach is likely to be applicable successfully to similar situations where scattering and other noise sources are a typical bottleneck to geophysical data acquisition on landslide bodies.

1. Introduction

The Vajont rockslide (North-Eastern Italy) is one of the best known and most tragic natural disaster induced by human activity, and is one of the largest catastrophic slope failures of the past century. On the 9th of October 1963 about 270 million m^3 of limestone, mudstones and marls slid from Mount Toc, in the North-Eastern part of the Veneto Region, Italy, into a large artificial reservoir built few years earlier for electricity production. The impact induced a water wave that overtopped the dam (the tallest in Europe at that time) and killed more than 2000 people in the valley of the Piave river downstream (Fig. 1). This landslide is one of the most famous erroneous estimation in geology history, due not only to its tragic consequences, but also to its particular behavior. The catastrophic failure was in fact preceded by a phase of accelerating creep, clearly related to the reservoir water level variation tests. The appearance of an M-shaped tension crack on the southern slope of Mount Toc, 1 km wide and 2.5 km long, foretold in fact the oncoming failure several months before the event (Müller, 1987). Despite this clear evidence, technicians and experts of the time remained anchored to the existing studies (Boyer, 1913; Dal Piaz, 1928) hypothesizing the presence of a very large and slow moving landslide that could be controlled during the reservoir operations. The total cost of the tragedy exceeded US$16 million of the time and the US$100 million dam and relative reservoir were abandoned just after been built (Superchi et al., 2010).

The Vajont landslide was intensively studied immediately after the tragedy by several international research teams (e.g. Carloni and Mazzanti, 1964a, 1964b; Frattini et al., 1964; Kiersch, 1964; Müller, 1964, 1968). Over the past decades other contributions came from new field observations (Semenza, 1986; Mantovani and Vita-Finzi, 2003). In spite of these research efforts, the landslide morphological and structural controls, in terms of failure mechanisms and dynamics, are not yet completely understood. The very large literature on the Vajont case (see e.g. Superchi et al., 2010 for a recent review) shows that most of the recent studies for re-evaluating the failure mechanisms were conducted on the basis of old borehole data, re-elaborated with

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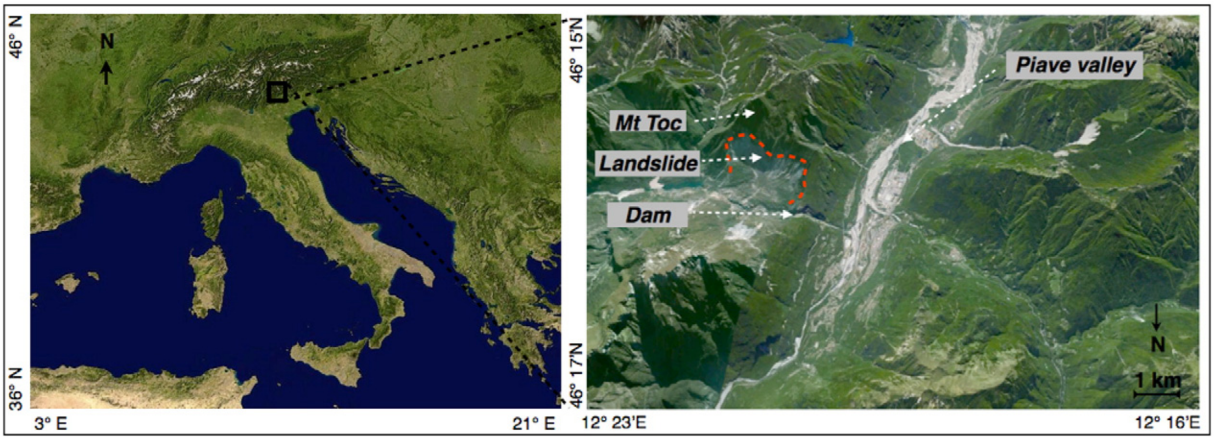

Fig. 1. The Vajont Mount Toc landslide and the Piave river valley, N–E Italy. The dotted red line shows the extent of the landslide detachment area.

new methods and techniques for rock mass analyses (Hendron and Patton, 1985; Semenza and Ghirotti, 1998; Semenza, 2010).

Modern investigations of landslides have increasingly adopted non-invasive (geophysical) techniques (for a review, see e.g. Jongmans and Garambois, 2007). Among the most commonly used methods are: geoelectric (Suzuki and Higashi, 2001; Lapenna et al., 2005; De Vita et al., 2006; Nguyen et al., 2007; Piegari et al., 2009; Tric et al., 2010) and seismic (Heincke et al., 2006; Stucchi and Mazzotti, 2009; Romdhane et al., 2011; Gance et al., 2012; Samyn et al., 2012; Malehmir et al., 2013). More limited use has been made of GPR, sometimes in combination with other methods (e.g. Carpentier et al., 2012), possibly as a consequence of a depth of penetration too limited to reach targets of interest in landslide studies (e.g., the slip surface). The use of multiple geophysical techniques and interdisciplinary data integration has been advocated and practiced with variable degrees of success, using geoelectrics and GPR (e.g. Göktürkler et al., 2008), geoelectrics and electromagnetics (e.g. Godio and Bottino, 2001; Schmutz et al., 2009), geoelectrics and seismics (e.g. Jongmans et al., 2000; Godio et al., 2006; Heincke et al., 2010; Grandjean et al., 2011) and even wider multi-disciplinary approaches (e.g. Bievre et al., 2012).

While of course geometries and geological structures vary widely between case studies, and so vary the specific requirements of non-invasive characterization, some general guidelines can be drawn, particularly for the most commonly used methods, i.e. seismic and geoelectric:

- Seismic can provide key information on landslide structure, provided that resolution and penetration issues are properly tackled in an environment made difficult by scattering induced by the damaged soil/rock sliding body.
- Seismic can also provide information on the mechanical properties of the rock mass, of course with some important caveats: (a) P-wave velocity may depend more on water-saturated conditions than on rock mechanical properties; (b) elastic moduli derived from seismics are inherently small-strain moduli, thus their direct translation into rockmass elastic properties or even worse mechanical resistance properties shall be approached with great care.
- Geoelectric is generally easier to deploy along steep hillslopes and can give, like seismic does, information on the system's structure. However, one should always recall that the presence of water is the single most important affecting soil and rock electrical properties. As water is also a critical factor in slope stability issues, this

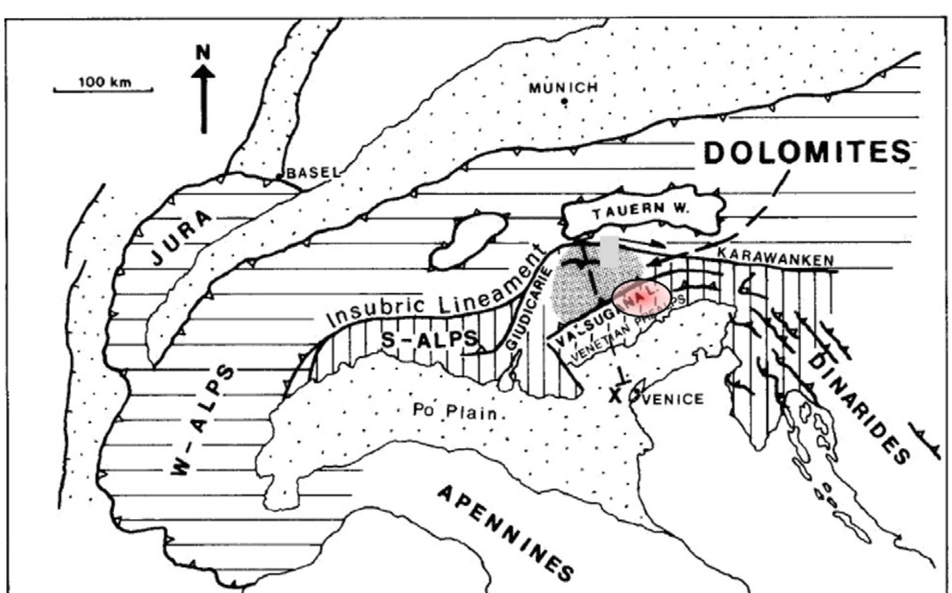

Fig. 2. Techtonic map of the Alps. The red area marks the zone of interest, in the Southern Alps domain (from Doglioni and Bosellini, 1987, modified).