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REFLECTION SEISMIC AND SURFACE WAVE ANALYSIS ON COMPLEX HETEROGENEOUS MEDIA: THE CASE OF MOUNT TOC LANDSLIDE IN THE VAJONT VALLEY

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ABSTRACT

In the framework of the Research Strategic Project Geo-Risks "Geological and hydrological processes: monitoring, modeling and impact in the North-East Italy", a seismic reflection survey and surface waves analysis were performed on the Mt. Toc landslide in the Vajont Valley, Italy. The aim of the geophysical measurements was to obtain a 2D geophysical model of the entire landslide body down to the sliding surface depth and the characterization of rock seismic velocities. Due to the critical environment, another aim of the project was also to explore the feasibility and limitations of these geophysical tools in large landslide studies.

The seismic reflection survey was conducted along two lines: L1 and L2, that are 510 and 322 m long respectively, with a - 'Vibroseis' - operating in the vertical mode (P wave) and vertical geophones. L1 was also acquired with - 'Vibroseis' - in horizontal mode (SH) and horizontal geophones.

The Frequency Time Analysis of surface wave was also adopted get another independent estimation of seismic velocity profile (shear wave) of the landslide body. For the surface wave study a 250 Kg drop source was used, in order to generate low frequency excitation. The large amount of recording channels furnished an image of the subsoil for the entire landslide body down to the target depth. Results are in good agreement with the borehole data and geological interpretations. Shear and compressional wave profiles allow a comparison with rock mechanical properties to be used in future rupture and slide simulations.

Key words: *Reflection seismic; Refraction seismic; FTAN; P-wave; S- wave; landslide*

INTRODUCTION

Italy's Vajont rockslide is one of the widely known and most tragic examples of a natural disaster induced by human activity. It is commonly considered as a reference event for risk evaluation, as well as for rock mechanics studies, as its study laid the basis of modern Engineering Geology. The 9 of October 1963 a catastrophic landslide occurred on the northern slope of Mount Toc (Vajont valley, Northern Italy). The landslide was induced by an artificial reservoir designed for electrical production. A rock mass of approximately 270 million m^3 collapsed into the reservoir generating a wave that surmonted the dam and swept into the - 'Piave' - valley below, causing the death of approximately 2000 people. At that time, over US$16 million was paid in civil lawsuits brought in respect of personal injury and death. The bibliography on Vajont (Superchi *et alii,* 2010; 2012) shows how many studies were conducted for re-evaluating the failure mechanisms in the last decades. Recently, due to the exceptional increment of new tools for publishing and sharing scientific papers, new knowledge methods and techniques for rock mass analyses are at our disposal. Nevertheless no deep geophysical seismic study of the entire landslide body has been conducted, due to the very difficult logistic problems of operating on the big landslide. This work represents a preliminary approach on this kind of geophysical characterization for the Mt. Toc landslide.

The techniques employed are reflection survey in P- and SH- wave together with controlled source surface wave analysis. In the spring of 2011 we acquired along the landslide body: N. 2 reflection seismic lines with a - 'Vibroseis' - source in P wave and vertical geophones; N.1 reflection seismic survey with 'Vibroseis' source in SH and horizontal geophones; N.1 surface wave seismic survey with a heavy drop-weight source and low frequency geophones.

Despite the critical landslide environment, the large amounts of active channels, the short receiver interval and appropriate seismic sources allow a satisfying imaging of the landslide structure. Results are in good agreement with borehole data, geological interpretations and mechanical properties of rocks, as estimated by other research groups.

GEOLOGICAL SETTINGS

The study area is located in the South-Eastern-Alps that, including the Dolomite region, are separated from the Orogenic wedge of the Alps s.s. by an important fault system known as the Insubric (or Periadriatic) lineament (Fig.1). The stratigraphic sequence outcropping in the Vajont and adjoining valleys ('Zemola' and 'Tuora' at East, 'Mesazzo' at the West), covers the upper Trias ('Dolomia principale') to Eocene ('Flysch'). It is formed by the following units: 'Dolomia Principale' formation, 'Soverzene' formation, 'Igne' formation, 'Vajont' limestone, 'Fonzaso 'and 'Socchèr' formations, 'Scaglia Rossa', 'Erto' Marls and Eocenic flysch. The Jurassic and Cretaceous rocks (limestones and marls mainly of the Socchér Formation), which were involved in the landslide movement, present various degrees of fracturing. These formations slid down along the "chair-like" bedding planes, causing the outcropping of the Fonzaso Formation (GENEVOIS & GHIROTTI, 2005). The failure was indicated to be principally confined within the 0.5-18 cm thick, clay-rich layers, which were observed to be continuous over large areas of the failure surface (HENDRON & PATTON, 1985). Fig. 2 shows a sketch of the 1963 landslide as reported by ROSSI & SEMENZA (1965).

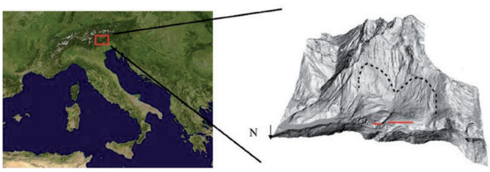

Fig. 1 - The studied area (N-E Italy) and the 3D hillshade lidar overview of the Northern slope of Mount Toc. In dotted black the landslide detachment, in red are the locations of the seismic investigations (see Fig. 3)

SEISMIC SURVEYS

The main aim of the project was to explore the feasibility and limitations of seismic methods applied to the study of a complex large landslide.

In Spring 2011 a combined reflection/refraction (P- and SH- wave) and surface wave survey was conducted to evaluate both the buried geometry after the tragic Vajont landslide and the physical-mechanical properties of the materials (PETRONIO *et alii,* 2011).

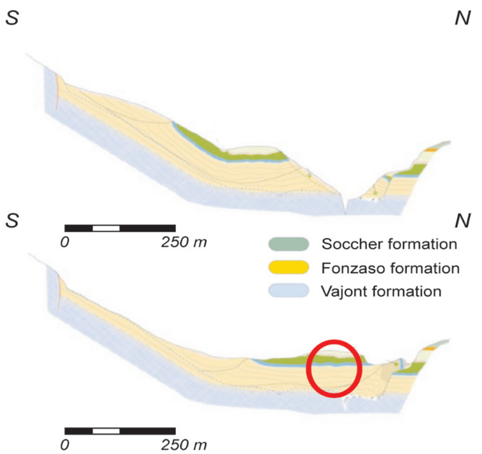

Fig. 2 - Schematic evolution of the 1963 landslide. Pre and post event, modified from ROSSI & SEMENZA (1965). Circle red is the investigated portion

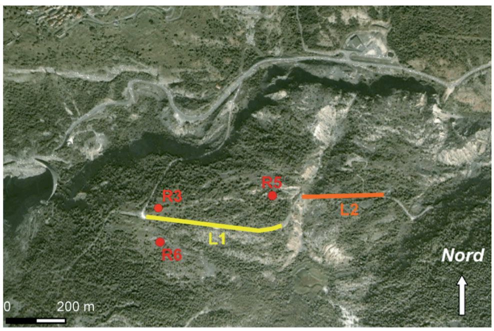

Fig. 3 - Position map. L1 and L2 are seismic reflection lines performed at the top of the landslide body. R3, R5 and R6 are post-event boreholes used for data correlation

REFLECTION SURVEY

The seismic lines location was forced by the very difficult logistical site conditions, especially in terms of source access difficulties, complexity of the landslide main body environment and study's needs. The aim was mainly addressed to a feasibility evaluation of the seismic method in such a peculiar and complex environment. For these reasons we used a large number of recording channels with short trace interval in fixed spread configuration. This approach leads to obtaining an high spatial density, mandatory for applications on such highly heterogeneous fields. Seismic line acquisition parameters are reported in Tab. 1. Data processing sequence is reported in Tab. 2.

The reflection analysis on single common shot gather reveals a complex wavefield; beyond first arrivals, clearly observable even at large offsets (400 -500 m), significant ground roll is present. Reflected events are detectable in many common-shot gathers, even if they present complex patterns and limited lateral continuity (Fig. 4). We perform cdp stack, pre-stack time migration (Fig. 5) and depth conversion.

P-wave reflection seismic

L1

256 ch., 10 Hz z (fixed spread), 2 m trace interval, length 510 m
125 shots (vibroseis upsweep 14 s, 5-250 Hz)
sampling rate 1 ms

L2

162 ch. 10 Hz z (fixed spread) – 2 m trace interval, length 322 m
81 shots (vibroseis upsweep 14 s, 5-250 Hz)
sampling rate 1 ms

SH-wave reflection seismic

L1

113 ch. 10 Hz x (fixed spread) – 4 m trace interval, length 448 m
113 ch. 10 Hz y (fixed spread) – 4 m trace interval, length 448 m
50 shots (vibroseis upsweep 14 s, 5-250 Hz)
sampling rate 1 ms

Tab. 1 - Reflection seismic acquisition parameters

1. *Format from SEG2 to SU*
2. *Cross-correlation with ground force signal*
3. *Preliminary editing*
4. *Vertical stacking*
5. *Assign geometries (input source and receiver locations)*
6. *First arrival picking*
7. *Spherical divergence recovery*
8. *Predictive deconvolution*
9. *First arrivals muting*
10. *Frequency filtering*
11. *Surgical muting (removal of groundroll)*
12. *Static correction*
13. *Notch filter (50 Hz only for bad trace)*
14. *Sort into CDPs (re-order traces in common midpoints) and binning*
15. *Velocity analysis*
16. *NMO correction*
17. *CDP stack*

Tab. 2 - Processing flow

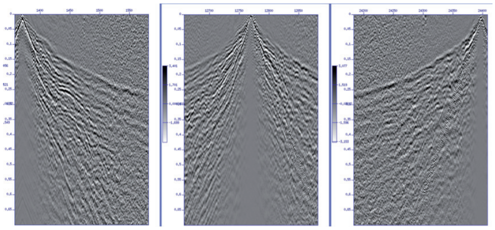

Fig. 4 - L1 data example: common-shot gathers (P wave)

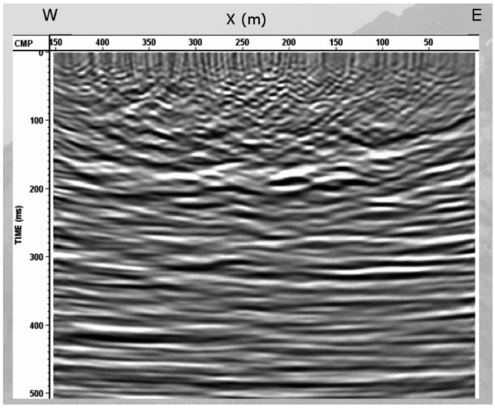

Fig. 5 - L1: Kirchhoff pre-stack time migration

SURFACE WAVE SURVEY

Surface wave analysis on Mt. Toc landslide was

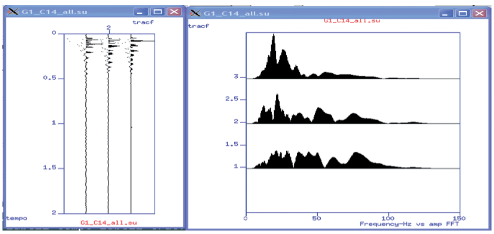

Fig. 6a - Weight drop data recorded by 1 Hz 3C geophone. 3C seismograms (1=inline H, 2=crossline H, 3=Z) and spectra: a) near offset (top)

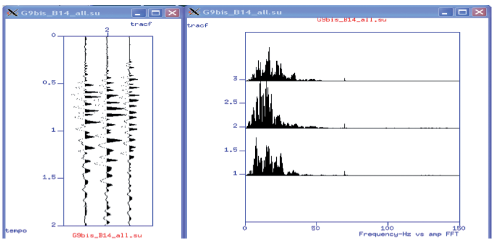

Fig. 6b - Weight drop data recorded by 1 Hz 3C geophone. 3C seismograms (1=inline H, 2=crossline H, 3=Z) and spectra b) far offset data (bottom):

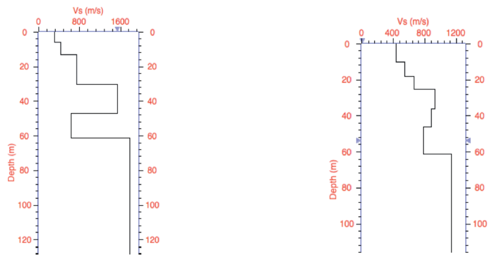

Fig. 7 - Example of 2 FTAN solutions for eastern and western receivers on Mt. Toc landslide

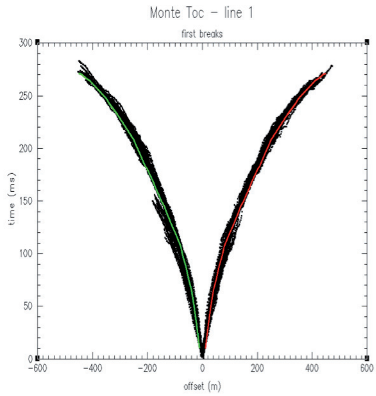

Fig. 8 - L1 (P-wave): first break picking

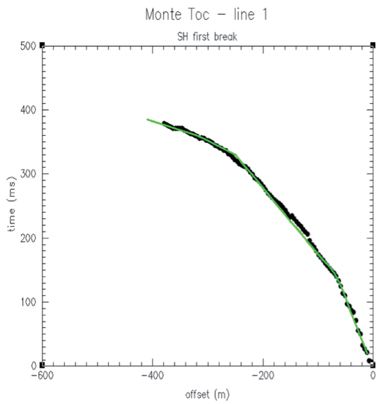

Fig. 9 - L1 (SH-wave): first break picking

performed by the use of a weight-drop controlled source. We adopted a 250 kg weight release by the arm of a crane at 6, 10 and 14 meters of height at 9 different locations along the L1 line. Seismic signals were recorded along the L1 line by 72 vertical geophones (4 m of trace intervals) with a natural frequency of 4.5 Hz along a portion of the L1 line and by 3 low frequency vertical receivers with natural frequency of 1 Hz, located at fixed positions (Fig. 6).

Low frequency receivers were used to perform a surface wave dispersion analysis (Nazarian *et alii*, 1983) with the FTAN technique (Frequency-time analysis as in Dziewonsky *et alii*, 1969; Levshin *et alii,* 1972, 1992; Knopoff, 1972; Knopoff & Panza, 1977; Nunziata *et alii*, 1999). Figure 7 shows the structure models as results of the Hedgehog non linear inversion adopted (Valyusv *et alii*, 1968; Panza, 1981; Boyadzhiev *et alii,* 2008).

REFRACTION SURVEY

P- and SH-velocities were computed from first arrivals recorded during the acquisition of the P- and SH-wave reflection survey along the L1 line.

Fig. 8 and Fig. 9 show the first arrival pickings performed on P- and SH-wave, respectively. Direct modelling was adopted to obtain simplified 1D velocity models used to convert time to depth reflection data and to support the data interpretation.

DISCUSSION AND CONCLUSIONS

Shear waves velocities of seismic refractions were compared with the velocities as derived by surface waves analyses. Fig. 10 shows the line drawing of L1 line with the superposition of seismic velocity models and boreholes data.

Surface wave analyses such as FTAN, as opposed to refraction seismic, was able to recognize shear wave velocities inversions. As the example of Fig. 7 shows, the velocities inversion at 50-70 m depth is in very good agreement with an expected level of fractured layers of the Soccher formation. This will play a relevant role in mechanical interpretation of the landslide, since the identification of shear and compressional wave allows the estimation of the Poisson ratio on site to be compared with lab analysis.

Figure 11 shows the interpretation of the L1 line guided by two borehole information.

Ferri *et alii* (2011) performed uniaxial and triaxial compressive tests on rock specimen to evaluate strength and elastic properties of the Mt. Toc landslide sequence. To perform on site mechanical estimation with geophysics is crucial, due to the representativeness limits of specimen geotechnical characterization at the landslide scale.

In Fig. 12 Poisson's ratio values obtained from laboratory measurements are compared with dynamic

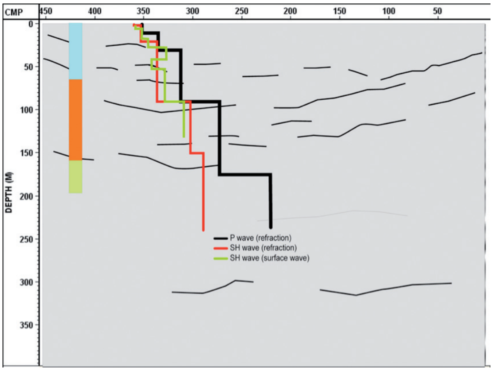

Fig. 10 - L1 line depth section with velocities profiles. in black Vp, in red Vs from refraction, in green Vs from surface waves. On the left the R3 borehole stratigraphy with in blue the 'Soccher' formation, in orange upper fractured 'Fonzaso' formation, in green lower 'Fonzaso' unit

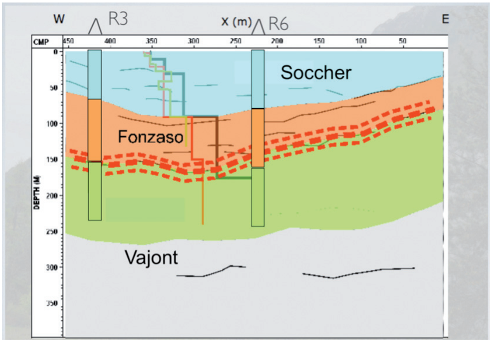

Fig. 11 - Interpretation of seismic line L1. R3 and R6 are boreholes used for correlation. In blue the Soccher formation; in orange Fonzaso upper formation, in green lower Fonzaso formation, in grey the Vajont Formation. Lines profiles are as above in black Vp, in red Vs from refraction, in green Vs from surface waves. In dashed thick red the sliding surface

values computed by seismic velocities. Static and dynamic values present interesting relationship, especially for the rupture zone characterization.

The very detailed reflection/refraction seismic together with surface waves methodologies, proved to be able to characterize the seismic properties of the Vajont 1963 landslide mass. These results are particularly relevant if compared to the hard logistic environments of the large landslide. Despite the difficult geophone coupling and limited sources employments, the geophysical surveys show good agreement with borehole data and allow a 2D imaging of the shear zone. In particular the joint use of very detailed refrection/refraction seismic and surface waves analysis seems to considerably improve the subsoil mechanical evaluation and are for these reasons promising tools for others large landslide case studies.

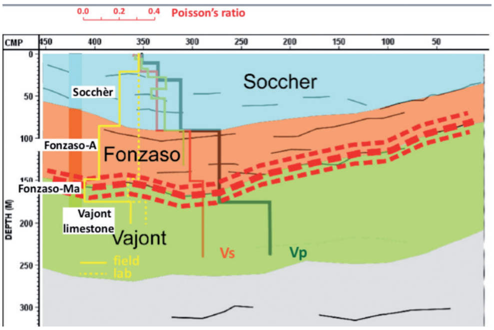

Fig. 12 - Static and dynamic Poisson's ratio comparison on Fig. 10

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