PRELIMINARY SEISMIC SURVEY ON THE UNSTABLE SLOPE OF MADESIMO (NORTHERN ITALY)

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Abstract

Diverse non-invasive seismic techniques are used to gain a fundamental knowledge of a complex unstable slope in the Italian Central Alps. A recent detailed geomorphological survey has proved the slope is affected by a deep gravitational deformation accompanied by superficial landslide phenomena, debris avalanches, soil creep and infrastructure damages. As the unstable slope directly threatens the popular ski resort of Madesimo, the risk associated to a possible collapse may be very high. Hence new efforts are required to define the geological and physical model of the slope, and to comprehend its dynamic and cinematic behavior.

Recently, preliminary 2D seismic investigations have been carried out at the slope toe, where a supposed sliding surface can be more easily detected, the slope is more gentle and a road offers the possibility to bring the seismic equipment close to the survey line. A shotgun and a 72-channel system assembled by combining equipment from two different manufacturers have been used to perform a reflection/refraction survey. P-wave first arrivals have been inverted with the main purpose of delineating the interfaces between weathered and massive rock and the velocity gradients associated with different fracturing degrees of the rock slope. The same dataset has been also processed according to the Multi-channel Analysis of Surface Waves (MASW) methodology. Surface wave analysis has been used to characterize the slope with S-waves, thus providing complementary information with respect to the refraction survey, as well as to verify the presence of velocity inversions. Reflection data have been processed to better identify the acoustic discontinuities within the slope and to extend the penetration depth of the previous seismic techniques. The processing sequence involves basic steps with no multichannel operations to avoid introducing artifacts in the seismic section.

Seismic results have been jointly interpreted with the support of the geological information gathered by superficial surveys.

Introduction to the Problem and Geological, Geomorphological Setting

The Alpine region is widely affected by large landslides and Deep Seated Gravitational Slope Deformations (DSGSD), involving large sectors of the slopes and in some cases leading to catastrophic phenomena. Beside tectonic and lithological factors, the slope debutressing following the Quaternary deglaciation and the current permafrost degradation played an important role in promoting valley flank collapses (Dramis et al., 1995; Ballantyne, 2002; Ambrosi and Crosta, 2006; Agliardi et al., 2009). In this respect, a seismic survey may supply detailed information about the thickness of slope involved in the mass movement, along with the geometry of rupture surfaces that are crucial elements for understanding the mechanic and the kinematics of the phenomenon (Jongmans and Garambois, 2007).

The study area is located in the Italian Central Alps (Sondrio) along the left hydrographic slope of the Scalcoggia Valley that descends from Mount Mater (3023 m a.s.l.) to the very popular ski resort of Madesimo (1550 m a.s.l.) (Fig. 1). The regional geological setting is related to the Pennidic Nappe arrangement, characterized by the emplacement of sub-horizontal gneissic bodies resulting from the Mesoalpine isoclinalic folding of crystalline basements, and separated by matasedimentary cover units. The tectonic contact gently dips to E–NE. The studied slope lies in the area of the contact between the Suretta and Tambò Units.

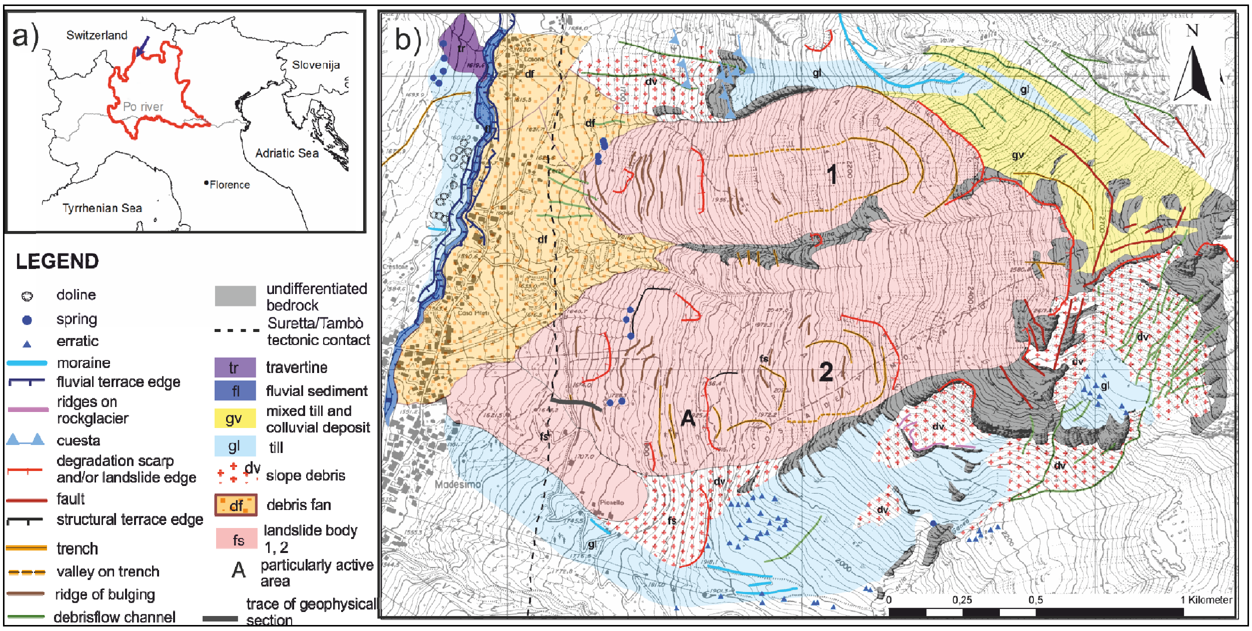

Figure 1: (a) Study area location and (b) simplified geomorphological map of the Mater Mount slope. Nappe tectonic contact according to CROP (1988).

A recent detailed geomorphological survey has revealed that a large sector of the slope is affected by instability processes (Fig. 1b), as also denoted by frequent infrastructure damages.

Specifically, two main landslide bodies (labeled 1, and 2, Fig. 1b) are delimited by scarps and well developed deep trenches from an altitude of 2650 m a.s.l. The work focuses on the southernmost body which reveals the most critical evidence of recent activities, the greater potential for unstable volume and the highest associated risk. The few rock mass outcroppings are intensely fractured and frequently affected by rock fall phenomena. The slope is mainly constituted by slope debris and till, both affected by creep and flow phenomena. Down-slope, secondary structures such as trenches, counterscarps and ridges mainly oriented N-S, break the continuity of the landslides body. At the altitude of about 1750 m a.s.l. an alignment of springs are found.

Debris fans develop at the confluence of minor streams in the main valley.

The thickness of the unstable body is not yet well defined, as well as its implication in a deep-seated gravitational deformation process.

To get a clearer understanding of the phenomena involved and on the basis of the above outlined geological and geomorphological setting, a seismic reflection-refraction profile was planned to investigate possible targets up to 100 m depth along the trace shown in Figure 1b, using an off-end configuration with 72 geophones and a seismic gun as energy source. To help choose the acquisition parameters, seismic rays were traced through a landslide model consisting of three nearly horizontal layers emerging along the slope at different points (the maximum depth of the deepest layer was 150 m). Computed traveltimes indicate a wider optimum window shooting downhill, and an offset of the order of 100 m to record non interfering refraction and reflection events. Source and receiver intervals were set to 2 m and the roll-along method was carried out manually every 10 shots, with a maximum in-line offset of 20 m.

To allow the refraction from the lowest layer to be recorded at a sufficient number of receivers for refraction and tomography analysis the maximum offset was extended up to 160 m, and different reverse shots were acquire along the profile for the velocity determination.

Reflection Seismics

One of the principal aims of the seismic acquisition is to determine the potentiality of reflection seismic to obtain information for the shallow layers in cases of unstable slopes, where the highly heterogeneous subsurface and the problematic coupling of sources and receives increase the difficulties of the reflection methodology (Jongmans and Garambois, 2007). In this context, the signal/noise (S/N) for the reflection events on the recorded data can be very low, possibly affecting the processing strategy or, at worst, the success of the whole survey.

To assess whether or not reflection seismic is able to give a reliable image of the subsurface at the site of Madesimo, we decided to apply a processing sequence that consists of very basic steps. We thus avoided multichannel filtering operations to separate the surface wavefield from the body waves or to attenuate some of the noise present, so as to be sure that no artifacts are introduced in the seismic section.

The acquired data were checked on a shot by shot basis at the beginning of the processing, zeroing out approximately 8% of the recorded traces that were considered too noisy (473 of a total of 5673 traces).

Nominal binning is 1 m, but to enhance the S/N we chose a bin size of 2 m, obtaining a medium coverage of 7000% at the expense of a reduced Common Depth Point (CDP) spacing on the stack section. Indeed, we considered a 2 m CDP spatial sampling adequate for our purposes.

First break picking for refraction statics computation was accomplished up to distances where the first kicks were clearly discernible. A single refractor model was used and the definition of the traveltimes pertaining to the different layers carried out on each shot. The velocity of the first layer was picked on selected records along the line and the estimated value ranges approximately from 500 m/s to 700 m/s. Statics application referred sources and receivers to a datum plane set at the elevation of the highest station, that is 1727 m a.s.l., using the computed refractor velocity as the velocity of replacement.

Mute functions were designed to remove the refracted arrivals prior to the statics application. A band-pass filter was applied to attenuate the lowest frequencies dominated by the surface waves and the frequencies above 70 Hz that gave a negligible contribution on the stack section, as suggested by the spectral analysis. Constant velocity stacks were used to build the stacking velocity field that was successively refined for a few points by the semblance analysis. Values close to 900 m/s along the line for the shallow times are the ones that yielded the best seismic section. An Automatic Gain Control (AGC) with a window of 100 ms and the stack of the Normal Move Out (NMO) corrected traces completed the processing sequence.

As a final step and for a preliminary evaluation of the results obtained, instead of performing a depth migration which is a complex and difficult task on this kind of data, we simply used the stack velocity field to convert the seismic image from time to depth (Fig. 2). This procedure is theoretically erroneous, but gives the opportunity to correlate the events visible on the seismic image to the results from other geophysical techniques and to the geological/geomorphological knowledge available.

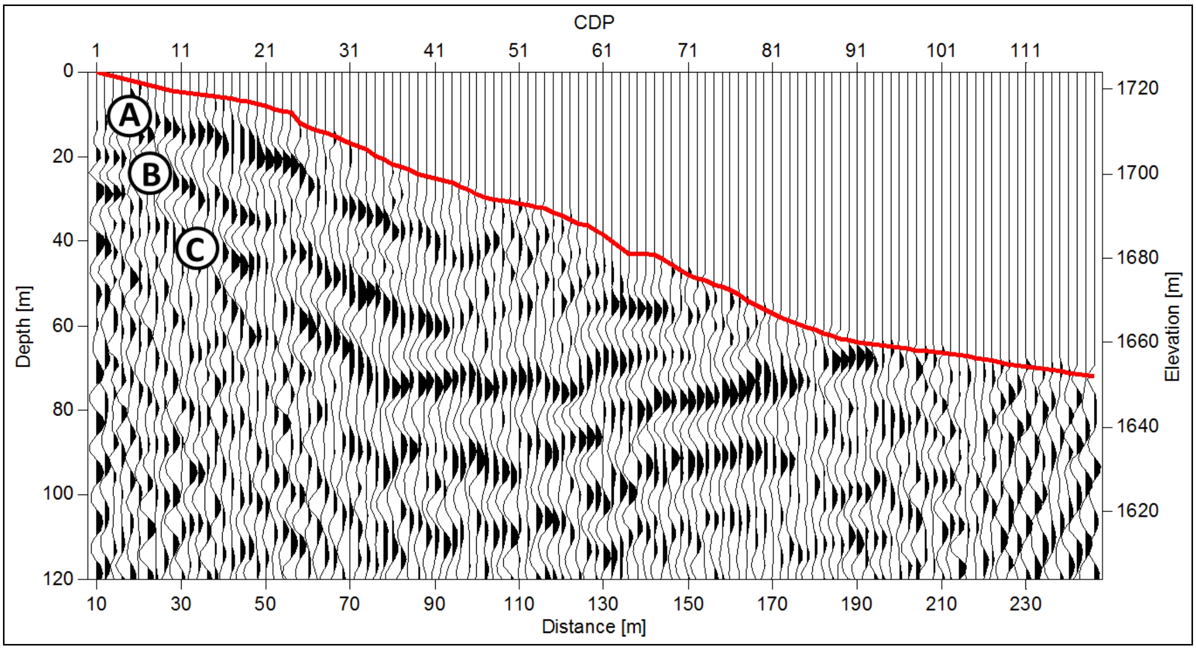

Figure 2: Stack section obtained at the end of the simplified processing sequence described in the text. The red line corresponds to the topography. Labels A, B, and C are interpreted layers, see text for details.

Refraction Seismics

Although the acquisition was designed to collect reflection data with an off-end spread, a number of additional shots were fired at points along the cable and from the opposite side to provide both forward and reverse traveltimes. First arrivals were manually picked on the entire range of the source-receiver distances, i.e., about 2 to 150 m. Picking up to 80 m was relatively easy and reliable while data from 80 to 150 m data are sometimes disturbed by such strong noise that many traces were not picked. Nevertheless, the number of available shots was high enough to ensure a redundant data coverage of the seismic profile up to the longer offsets.

First arrivals were analyzed with a reciprocal method to obtain a preliminary interpretation consisting of a three layer structure. A thin layer (corresponding to label A, Fig. 2) with a thickness varying from 2 to 6 m and a velocity from 400 to 600 m/s covers a 30 m thick layer characterized by a velocity of about 1200 m/s. Below this layer a much faster formation is found with a velocity of about 3100 m/s.

This model was assumed as the input model for a tomographic inversion from which we obtained the result shown in Fig. 3. Compared to the initial model, tomography tends to produce a small increase of the first layer thickness and seems to smooth the velocity transition from the second to the third layer. This is consistent with the observation that the time-distance graph of the first arrivals does not actually show a sharp slope change from second to third refraction, so that the assumption of a three layer structure is somehow questionable. To reduce the constraints of the tomographic inversion and to explore the stability of the final model, two different initial models were also tested. One model was generated by removing the second and third layers of the initial model and introducing a second layer with a vertical velocity gradient ($50s^{-1}$) below the shallow low velocity layer. For the second test, the low velocity layer was also removed and a single layer with a vertical gradient of $55s^{-1}$ was used. Results are very similar and only the output of the second test is shown in Fig. 4. The first layer structure is basically confirmed and quite stable in all the models and consistent with the one computed for refraction statics. The deepest layer at about 40-50m from the surface is also confirmed with all the initial models, with a velocity higher than 3200 m/s. The intermediate structure obtained from tomography when we assume a velocity gradient rather than a three layer model seems to be better interpreted if we split this part of the subsurface in two layers with velocities of about 1600 and 2500 m/s respectively. The geometry of the 2nd, 3rd and 4th layers in Fig. 4 is also more interesting than the one observed in Fig. 3 and shows a very good agreement with the most important reflections of the stack section (Fig. 5).

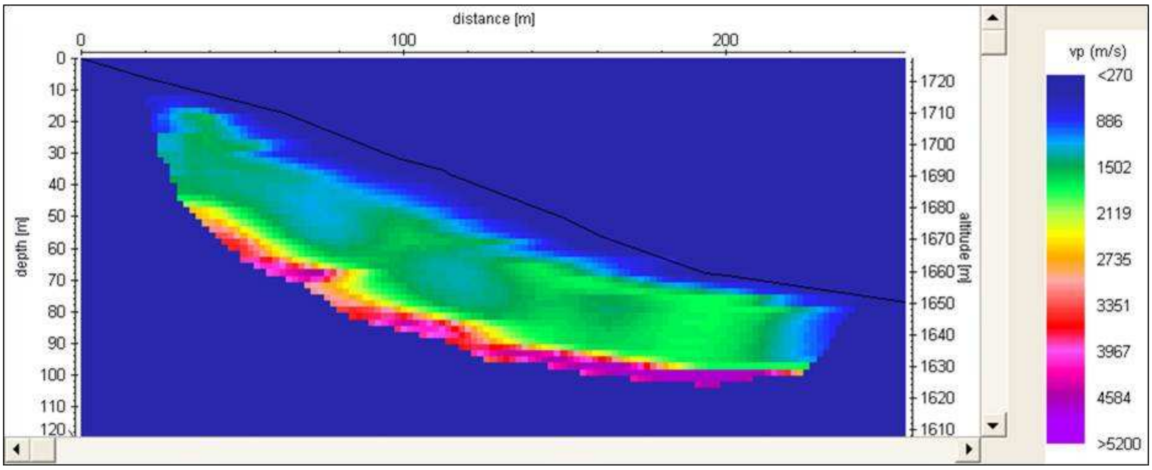

Figure 3: Refraction tomography (3-layer model).

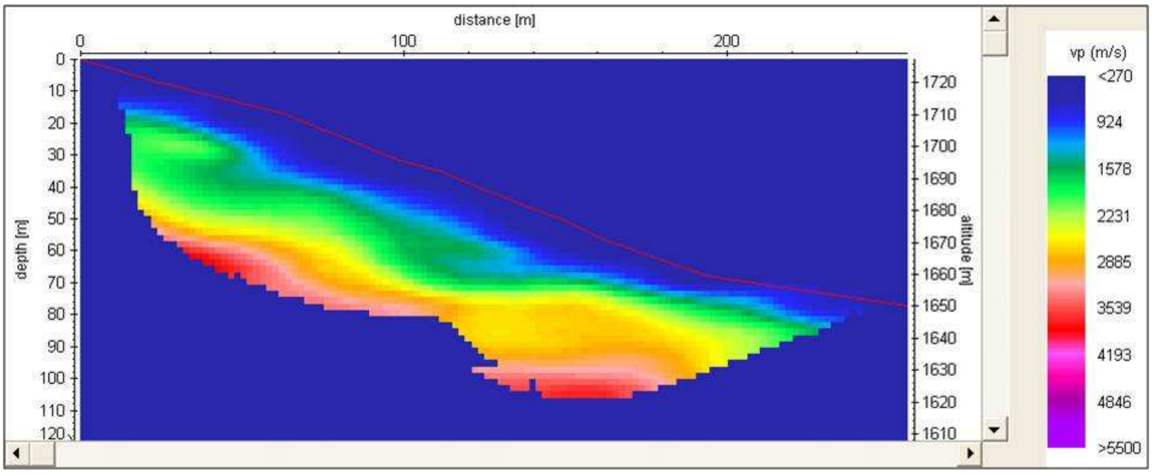

Figure 4: Refraction tomography (1-layer model with vertical velocity gradient).

MASW

Off-end shots planned for the reflection survey were analyzed in terms of ground-roll dispersion according to the MASW methodology (Park et Al., 1999). Preliminary shots fired at the beginning of the geophysical campaign to test the acquisition parameters were also employed. As a result, the MASW dataset consisted of different spread lengths (24, 48 and 72 channels with 2 m or 5 m geophone spacing) along with several in-line offset sources.

In agreement with one of the fundamental assumptions of the standard MASW method (Strobbia, 2003), only areas of the slope presenting layering parallel to the topographic surface (i.e., 1D earth model) were considered. To do so, outputs of the reflection as well as refraction investigations were taken into account. We deemed it reasonable to study portions of the survey line spanning approximately from 20 m to 100 m, and from 200 m to the end of the profile (although results of previous seismic investigation are less reliable at the borders - see Figs. 2 and 4).

Before determining the dispersion relationship, selected shots were analyzed to evaluate the S/N of the recorded surface waves. In general, noisy channels and P-wave refracted energy were observed at far offsets, and higher modes usually dominated the ground-roll. Both fundamental and higher modes very often displayed a discontinuous trend in time. This is likely due to the irregular topography associated with a chaotic propagation environment within the landslide body that gives rise to scattered energy outside the 2D plane of the survey. As a consequence, dispersion analysis performed in the frequency-wavenumber domain (Strobbia, 2003) was not straightforward. Moreover interference between modes usually manifested as up-going dispersion trends, and discontinuities of the medium made phase behavior complex.

Pre-processing of the data initially consisted of the removal of noisy traces as well as traces pertaining to the slope section not satisfying the 1D model assumption. Data were then low-pass filtered and refracted arrivals were muted. Finally f-K filtering was performed in an attempt to enhance fundamental mode energy and reduce higher mode interference. Nevertheless, reliable picking of dispersion curves over a wide frequency range was quite difficult. Generally, only the frequencies higher than 12Hz were picked with satisfactory confidence and this resulted in shear-wave velocity profiles along the seismic line covering a limited depth of investigation.

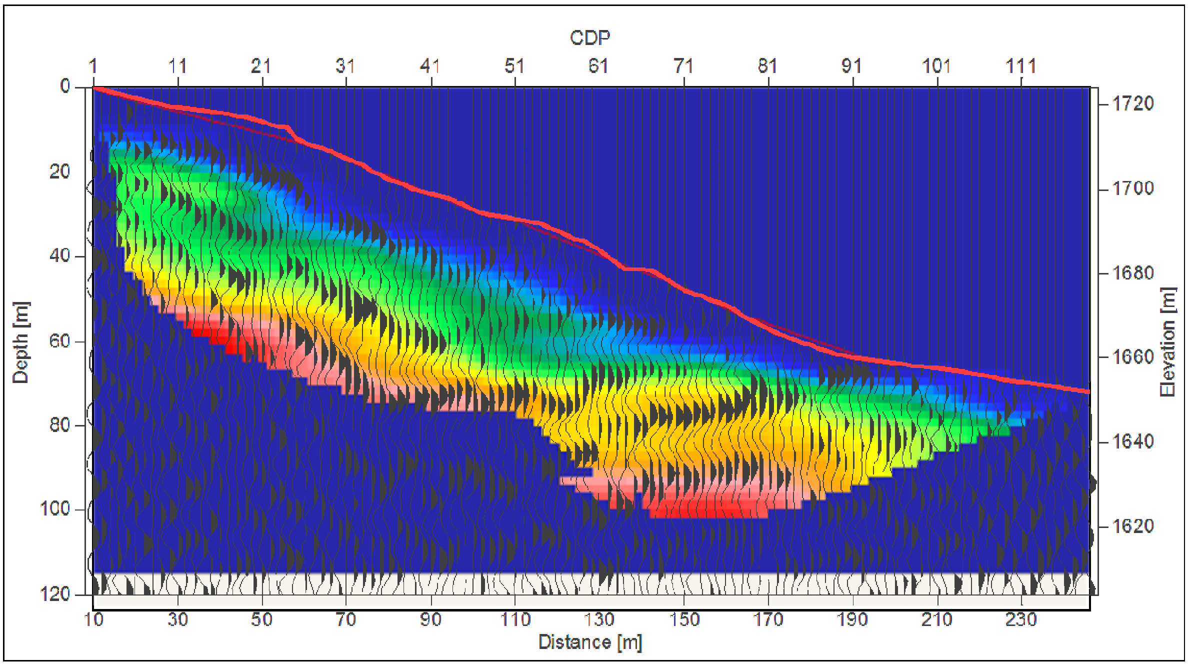

Figure 5: Final output with reflection and refraction results superimposed.

Discussion

Reflection and refraction seismic surveys converge in indicating subsurface discontinuities at comparable depths. The geometry of reflectors and velocity changes in seismic refraction tomography shows a high grade of similarity (Fig. 5). These results, assisted by geomorphological evidence, allow us to perform an integrated interpretation of the processed data.

When a 1-layer model with vertical velocity gradient is adopted, the refraction tomography survey indicates three layers beneath the thin low-velocity surface layer (Vp = 400-600 m/s) (Fig. 4). Specifically, these layers correspond to the velocity ranges 1400-2200 m/s, 2300-2900 m/s and > 3100 m/s. This subdivision into four layers is coherent with a geological model of the subsurface that, beneath the first weathered layer (whose bottom is reflection A in Fig. 2) consisting of slope deposits enriched in fine eluvial-colluvial material, supposes a layer composed by boulders of various sizes with interstitial voids, followed by a layer of densely fractured rock mass locally disarticulated, resting on a less disturbed bedrock.

In both seismic reflection and refraction investigations, both discontinuities B and C (Fig. 2) show a spoon-shaped geometry, pointing out to a rotational mechanism for the displacement the involved masses. The existence, at least in the portion of the landslide investigated by seismic survey, of more than one spoon-shaped discontinuity indicates that the failure (rupture) occurred in different parts of the slope. This is coherent with a multitemporal evolution of the Madesimo landslide that should be composed of different minor landslide bodies with their own state of activity. The geometric relationship between reflectors/refractors is a matter still under examination. It is worthy to note that the geometry of reflector C (Fig. 2) is consistent with the break in the topographic slope corresponding to the landslide foot.

Finally, the deepest seismic layer may correspond to fractured rocks with weak geomechanical behavior, potentially involved in a slow creep movement, e.g. that of DSGSD. The high velocity recorded at the slope foot (Fig. 4) suggests an irregular top of the bedrock and support this hypothesis.

The MASW method was found to add little value to the whole investigation process. This was largely due to the presence of a chaotic propagation environment presenting boulders of various sizes, voids and, in general, heavily fractured rock. As expected when dealing with unstable slopes, the assumption regarding the absence of lateral variations was often not valid. Therefore it was difficult to follow well-behaved dispersion trends of Rayleigh waves within the collected datasets.

Conclusions

The geophysical surveys performed on the Madesimo unstable slope allowed for the determination of the presence of a 4-layer structure (reaching approximately 60m depth), described in terms of layer thicknesses and P-wave velocities. Reflection and refraction seismic methods proved to be suitable methodologies for slope instability investigation, able to provide coherent information about the subsurface conditions. The output of these analyses, corroborated by a detailed mapping of the geological features on the surface, will be a useful tool to understand the kinematic behavior of the slope.

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