Engineering Geology 128 (2012) 23–29

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Characterizing landslides through geophysical data fusion: Example of the La Valette landslide (France)

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ARTICLE INFO

Article history:
Accepted 3 May 2011
Available online 10 May 2011

Keywords:
Landslide
Geophysics
Data fusion
La Valette

ABSTRACT

Many studies show that certain geophysical methods, such as seismic and electrical-resistivity imaging, appear to be well adapted for investigating the internal structures of landslides and understanding the related hydro-mechanical mechanisms. These are methods that allow the direct and non-intrusive measurement of acoustic (P) and shear (S) wave velocities and electrical resistivity (ρ), which are three physical parameters considered as essential for estimating the mechanical properties of moving reworked material. We applied these techniques to the La Valette landslide (Southern French Alps), a typical example of an intra-material landslide, carrying out measurements simultaneously along two profiles, 400 m and 300 m long and respectively perpendicular to and along the slide direction. We then used suitable inversion algorithms to estimate both the P- and S-wave velocity fields and the electrical resistivity field from the recorded data. The results, aided by field surface observations, show that a correlation exists between the state of the material and the seismic-velocity and/or electrical-resistivity data, thus confirming that the simultaneous use of the two methods provides complementary information on the geomechanical behavior of the landslide. More particularly, the seismic data provide information on fissure density variations and the presence of shear-bent material, whereas the electrical resistivity data provide information on the groundwater content. To enable a more integrated petrophysical interpretation, we applied a data-fusion strategy based on fuzzy subsets to the geophysical datasets. Through combining the tomograms we identified a surface layer of soft material along the two profiles; the bottom of this layer was also recognized in a borehole. From a methodological point of view, the results show the applicability of adopting geomechanical hypotheses as inputs of geophysical data fusion for identifying areas where sediment mobilization could occur.

1. Introduction

Many active landslides occur in the French Alps, particularly in clay–shale deposits (Malet, 2003) which form unstable areas characterized either by movements along discrete shear planes (Hungr et al., 2001) or by continuous deformation resulting from local factors such as steep slopes (>25°), weak mechanical properties of the ground, and moisture (Baum et al., 1998). The landslides generally involve heterogeneous clay-rich clastic material that is practically water saturated during the wet season. Earlier studies (Godio et al., 2003; Cutlac and Maillol, 2005; Grandjean et al., 2007) have shown that imaging such areas through a multi-method geophysical approach can increase the level of information.

The aim of the present study, which we focused on the La Valette site in the Southern French Alps, has been to develop an innovative approach for characterizing the geometry of subsurface clay-rich material susceptible to being reactivated, for example, during periods of heavy rainfall, as suggested by Flageollet et al. (1999). Knowledge of the volumes that could possibly be reactivated is critical information for landslide hazard assessment, and particularly for determining the final run-out distance (Dai et al., 2002). To achieve our objective, we used geophysical methods for identifying the uppermost layers likely to be affected by such sliding processes.

Seismic techniques are classically used for estimating the dynamic properties of rocks and soils (Crampin et al., 1980; Aki et al., 1982; Kahraman, 2002), and since they are non-destructive and easy to operate, they are increasingly used in geotechnical engineering. The adoption of geophysical methods to characterize sliding masses and reworked material and to estimate their extent is very helpful for assessing the integrity of potentially dangerous slopes, as shown by Leucci and De Giorgi (2006). Seismic methods have more recently been successfully tested for imaging unstable slope structures and, more particularly, for determining bedrock geometry (Glade et al., 2005; Jongmans et al., 2009). The methods are based on the direct measurement of acoustic waves, i.e. P-wave traveltimes, which are themselves related to P-wave velocities (Vp), one of three essential

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doi:10.1016/j.enggeo.2011.05.001

parameters for estimating the main mechanical properties of reworked material (see Schön, 1996). The second essential petrophysical parameter for estimating rock properties, and thus for understanding the mechanical behavior of landslides, is the shear-wave velocity (Vs), which gives an indication of the rock's stiffness and can also be inverted from Rayleigh wave dispersion analyses (Park et al., 1998; Stokoe and Santamarina, 2000; Park et al., 2005). The third parameter is electrical resistivity tomography, which can be used to estimate the electrical resistivity (ρ) of rocks and, knowing that this parameter is closely related to the water content, can indicate places where water saturation predominates (Lapenna et al., 2004; Naudet et al., 2008).

The use of these methods simultaneously at the same place is not very easy because of the accumulation of different types of information: combining the resultant parameter sets requires maximum coherence in the final interpretation. Analyzing and merging several geophysical parameters are not a trivial exercise and several studies have put forward interesting solutions such as coupling the inverse problems in a joint inversion (Schmutz et al., 2000; Gallardo and Meju, 2003). It is to overcome the complexity of such approaches that Grandjean et al. (2007) propose a fusion strategy based on the fuzzy set theory. The method allows different geophysical data to be combined in a unique set that integrates all pertinent information revealed by each inverted image (Grandjean et al., 2009). The advantage of using a data-fusion technique as opposed to a visual multi-interpretation method lies in the objectivity of the algorithms—the methodology is supported by a formal logical approach. The pertinence of the method lies in the coherent interpretation of multiple geophysical data to propose a geological or geotechnical diagnosis when few additional data (e.g. laboratory measurements) are available. The fuzzy logic approach enables one to take advantage of the multi-geophysical parameters in a complementary manner. The resulting images highlight the places where specific physical phenomena occur conjointly on the different datasets without being dependent on interpretation subjectivity. After promising tests carried out in different contexts (Grandjean et al., 2006, 2007, 2009), we used the approach on the La Valette landslide to identify the sliding mass.

La Valette (Figure 1) is located in the Ubaye Valley of the Barcelonette Basin (Alpes-de-Haute-Provence, France). The basin has characteristic badlands morphology with multiple erosion-incised V-shape gullies and flank slopes varying between 30° and 70°. The landslide is in Callovian–Oxfordian black marl, known as "Terres Noires" whose color varies from black to gray (Antoine et al., 1995). The slope surface is highly irregular and is affected by 0.5- to 1.0-m-deep kinematic tension cracks, as well as by surficial shrink/swell fissures, suggesting that the deeper layers are highly fractured. Several gullies, partly filled with heterogeneous weathered rock and debris, also incise the landslide. From a hydrological and geotechnical viewpoint, the landslide comprises two vertical units comprising a moderately stiff semi-permeable material (10 to 20 m thick) overlying a stiff impervious material considered as bedrock (Travelletti et al., 2009). The uppermost subsurface material is intensely fissured reworked black marl with a sandy–silty matrix and low plasticity. The landslide kinematics, with velocities of the order of one to several cm.day^{-1} is controlled by the hydrology; the deformation results from the rise of a perennial groundwater table and hence the development of positive pore pressures in the moving material. Groundwater fluctuations are controlled by water infiltration in both the soil matrix and the large kinematic cracks and fractures, as well as by recharge from the torrents bordering the landslide (De Montety et al., 2006).

2. Geophysical surveying

The geophysics consisted in a combined seismic and electrical tomography survey along two profiles, respectively 400 and 300 m long and designated T2 and L2 (Figure 1). Each method, from field acquisition to final data processing, is briefly described in the next sections.

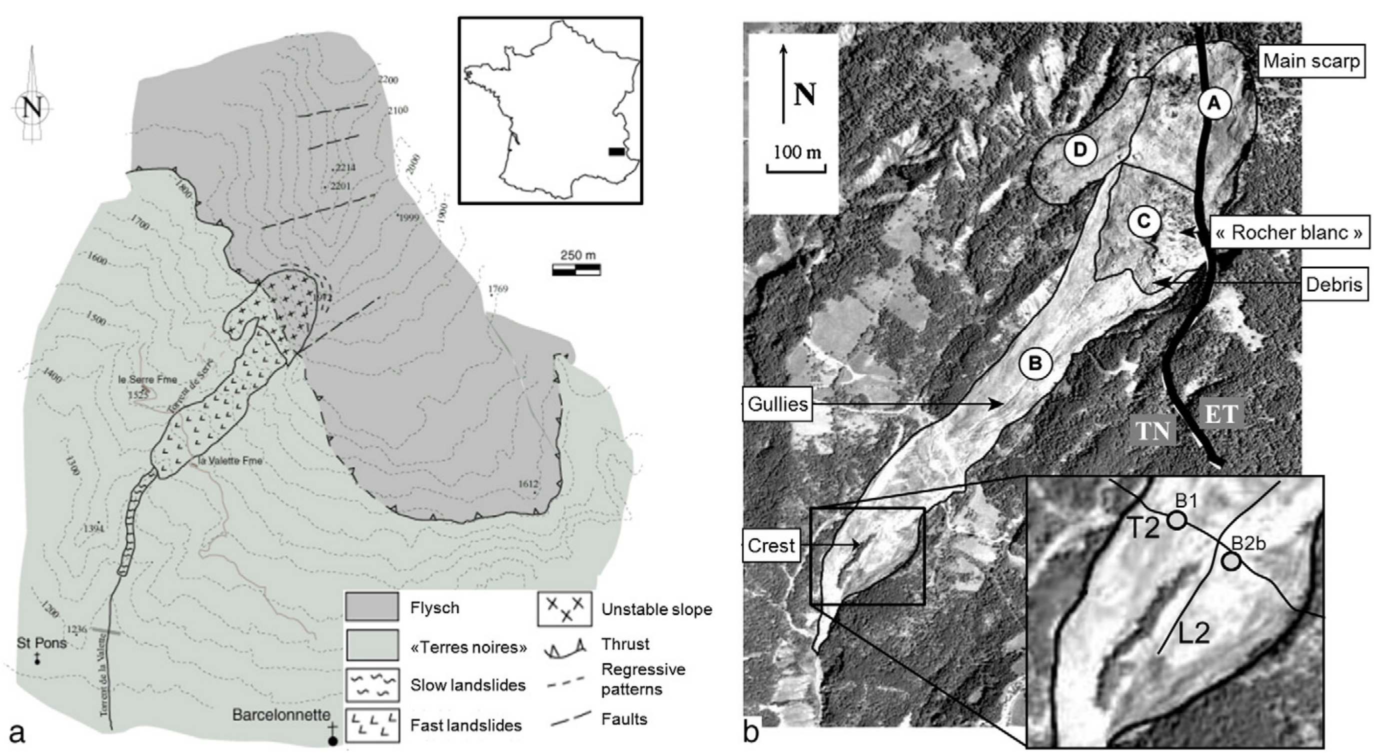

Fig. 1. a) Location map and general geology of the La Valette landslide (from Le Mignon and Cojean, 2002). b) Orthoimage of the La Valette landslide showing the main active zones. A: main scarp, B: active mudflow, C: main slope failure, D: new active area (from Casson, 2004), TN: "Terres Noires", ET: Embrunais thrusts. The black line marks the limit between TN and ET. The two geophysical profiles (T2: transverse; L2: longitudinal) are shown as black lines on the enlarged inset. B1 and B2b: boreholes drilled near profile T2.

2.1. Seismic P-wave tomography

The acquisition system consisted of a digital seismic unit controlling a 48-channel array of 10 Hz geophones and a handy-hammer source. The geophones were set at 5 m intervals along each profile with seismic shots being fired every 15 m. The data processing and inversion of the first arrival traveltimes were performed using JaTS seismic tomography software (Grandjean and Sage, 2004) which enables data filtering, traveltime picking and P-wave velocity (Vp) inversion. Fig. 2a and b show the Vp distribution along profiles T2 and L2, respectively.

2.2. Spectral analysis of surface waves (SASW)

SASW is of increasing interest within the geophysical community because it offers a non-invasive means of evaluating the soil shear modulus distribution with depth (O'Neill et al., 2003) and can be easily implemented along linear sections to obtain two-dimensional shear-wave velocity profiles (Miller et al., 1999). Before inversion, each seismic record needs to be transformed into a dispersion image (Park et al., 1998) from which the frequency-phase velocity curve (e.g. dispersion curve) is estimated. In laterally contrasted media, the dispersion images have to be computed with a more local approach with respect to the 1D assumption required by the Levenberg–Marquardt inversion method of Herrmann (2002). This issue is tackled by applying the 2M-SASW technique (Multifold Multichannel SASW; Grandjean and Bitri, 2006) to the same seismic data used previously for the P-wave tomography. Then, in order to obtain a 2D section, the 1D shear-wave velocity profiles inverted for each local dispersion curve are interpolated along the seismic line using a kriging algorithm. The reliability of the inverted S-wave velocity (Vs) profiles is provided directly by the diagonal values of the correlation matrix computed by the inversion algorithm. Fig. 2c and d shows the Vs distribution along profiles T2 and L2, respectively.

2.3. Electrical resistivity tomography

The electrical apparent resistivity profiles were acquired along the same profiles as the seismic survey by using a Wenner–Schlumberger array with an electrode spacing of 5 m. Data processing and inversion were carried out according to Loke (1994) through implementing a damped least-squared Gauss–Newton algorithm. Fig. 2e and f shows the electrical resistivity (ρ) distribution along profiles T2 and L2, respectively.

The reliability of the resultant geophysical tomographies representing the geophysical parameters Vp, Vs and ρ was quantified by means of

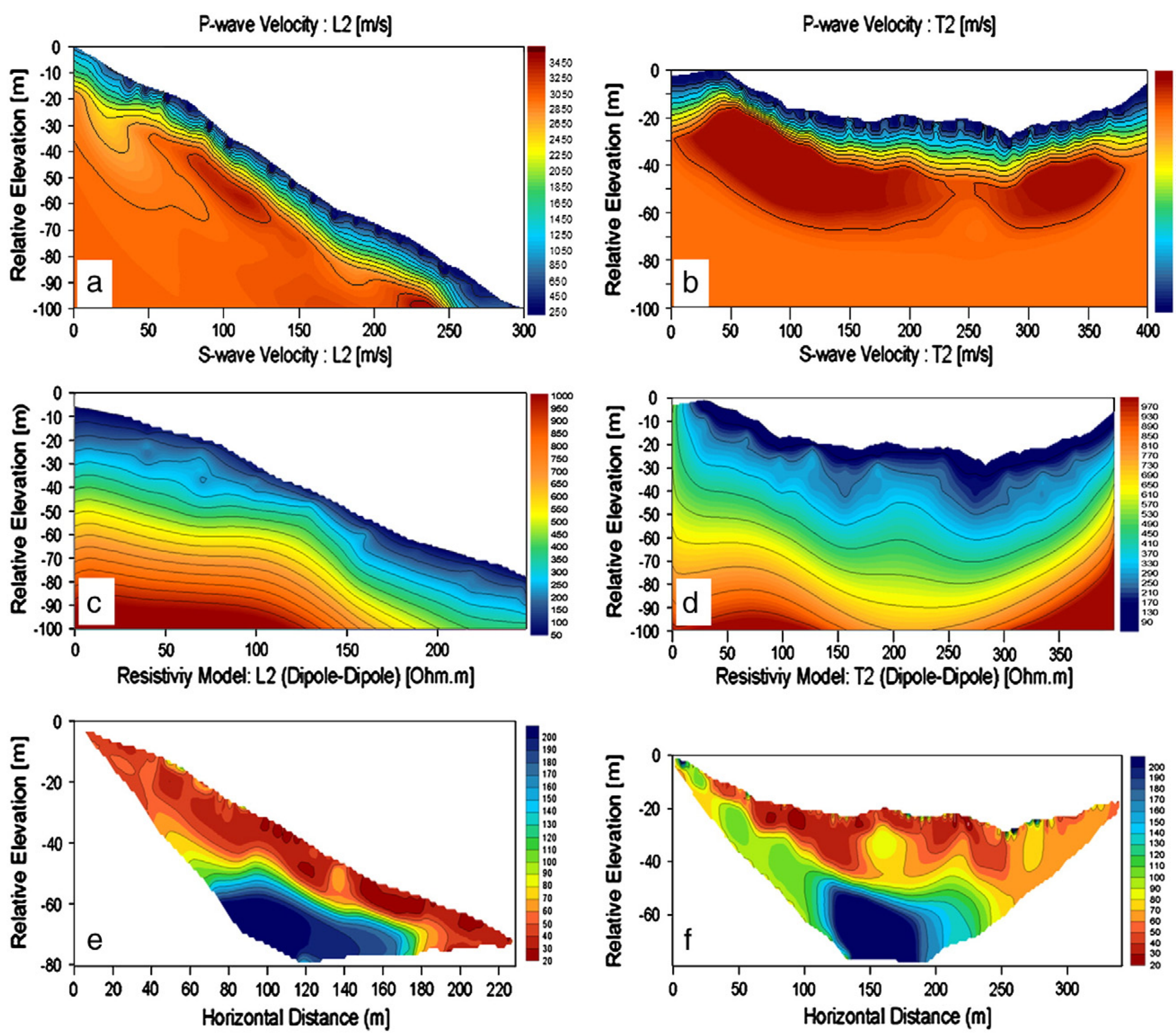

Fig. 2. 2D geophysical images along profiles T2 (b; d; f)) and L2 (a; c; e) for P-wave velocities (a; b), S-wave velocities (c; d) and electrical resistivities (e; f).

likelihood functions L as described in Grandjean et al. (2007), and respectively noted L_{Vp}, L_{Vs} and L_p. The main advantage of applying these criteria for estimating the reliability of inverted models lies in the normalization of such functions, each varying between 0 and 1 with increasing reliability of the geophysical parameters. Normalization processes were necessary to transform the inversion-algorithm generated functions, such as cost RMS functions, into likelihood functions.

Finally, a qualitative interpretation based on the three geophysical tomographies and two boreholes located next to the survey lines led to the identification of a slip surface between the moving mass and the bedrock (Travelletti et al., 2009). An interpreted geological model is shown in Fig. 3 with the borehole locations and the intersection of longitudinal profiles along the transverse profile T2.

2.4. Toward a geotechnical interpretation

This section aims to provide a more quantitative exploitation of the geophysical measurements. For a better identification of the less stiff zones, we integrated a new quantity in the study, i.e. the unconfined compressive strength (UCS). This quantity appears to be useful for determining soil strength (Moos et al., 2003; Zoback et al., 2003) and thus for determining instabilities within large landslides (Watters et al., 2000). Depending on the state of rock alteration, the UCS can be used to detect highly degraded rocks that could be easily mobilized during catastrophic rain events. As presented by Hoek and Brown (1997), the value of the UCS can be qualitatively linked to intact rock strength and/or weathering and alteration levels. Thus, by estimating the UCS through computation of the dynamic Young's modulus and empirical relationships, it can be used as a hypothesis parameter in the fuzzy logic fusion process. The dynamic Young's modulus can be defined, provided that the frequency range is greater than 10 Hz, by (Jaeger and Cook, 1976):

$$E_D = \rho v_s^2 \frac{3\left(\frac{v_p}{v_s}\right)^2 - 4}{\left(\frac{v_p}{v_s}\right)^2 - 1}. \qquad (1)$$

The correlation between dynamic and static Young's modulus has not yet been studied for the specific case of the Callovian–Oxfordian marls. There are nevertheless many general relationships linking these two quantities. Here we chose the empirical relationship proposed by Eissa and Kazi (1988) because it was inferred from experiments conducted on a wide range of rocks and it has a reasonable correlation coefficient of 0.84:

$$E_S = 0.74E_D - 0.82. \qquad (2)$$

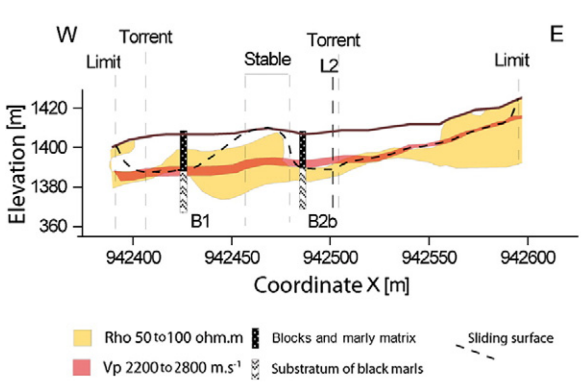

Fig. 3. Slip surface determined on profile T2 from a classical interpretation of the geophysical tomograms and borehole data.

Finally, a second relationship was used to estimate the UCS (Arslan et al., 2008). As with E_D–E_S, no relationship exists between Es and UCS for the specific case of marls. Also, no geotechnical test has yet been done on the UCS–Es relationship relative to the La Valette landslide, although some measurements were available from similar nearby landslides like Super-Sauze, Poche and Laval (Malet, 2003) as summarized in Table 1. These values were therefore used to calibrate the empirical relationship derived from a big panel of sedimentary rock analyses and proposed by Arıoğlu and Tokgöz (1992). We adjusted the exponent of this relationship to bring the computed UCS from the E_D given by Malet (2003) closer to the UCS observed for intact marls (Table 1).

The adapted empirical relationship of Arıoğlu and Tokgöz (1992) used in our study can therefore be expressed as:

$$UCS = (0.9709E_S)^{1.8350}. \qquad (3)$$

Consequently, using Eqs. (1) to (3), it becomes possible to compute the values of the UCS from the two velocity (Vp and Vs) tomograms.

2.5. Interpretation through data fusion

Interpreting geophysical data for geological or geotechnical applications raises important issues related to the uncertainties. Fortunately, various mathematical tools such as the probability, evidence and possibility theories enable data imperfection to be taken into account (Nifle and Reynaud, 2000). Here we shall consider the possibility theory in terms of an innovative approach to manipulate uncertainties related to geological and geomechanical interpretation. Basically presented by Dubois and Prade (1980) and fully described in Grandjean et al. (2007), the method is based on the formulation of belonging functions that express each geophysical parameter variation as a possibility value (Figure 4) indicating the level of reliability of a particular hypothesis; each observed geophysical parameter is thus related to a property of the ground material, which itself conditions the hypothesis. Once each function is defined according to available field observations or expert knowledge, the mathematical background developed in the “fuzzy set” theory provides different operators for mixing the possibility values. Likelihood functions can be integrated into the fusion process in the same way.

The different hypotheses formalized by the belonging functions can now be presented. From geomorphological observations and the tomograms computed in the previous sections, we were able to describe certain soil outcrops from a hydromechanical standpoint. These macro descriptions were then used to express three hypotheses (h_1 to h_3) associated with three possibility functions ranging from 0 to 1:

- **Hypothesis h_1** assumes that the soil strata are densely affected by fissures due to traction forces developed during the slide: its possibility π_1 is correlated with the variation of the P-wave velocity observed in the subsurface. From our geomorphological knowledge of the landslide, the soil strata is fissured if the P-wave velocity is less than 300 m.s^{-1} and non-fissured if the P-wave velocity is more than 1500 m.s^{-1}. The possibility is assumed to be linear between these two values.

Table 1
Experimental values of ED and UCS realized on similar neighboring landslides (Malet, 2003).

	Super-Sauze	Poche	Laval
E_D (Mpa) — intact marl	11230	11975	12250
UCS (Mpa) — intact marl	38	45	48
UCS (Mpa) — fractured marl	19	11	28
UCS (Mpa) — clay joints	6	3	5
UCS (Mpa) — computed from E_D using Eqs. (1) to (3)	38.86	43.95	46.60

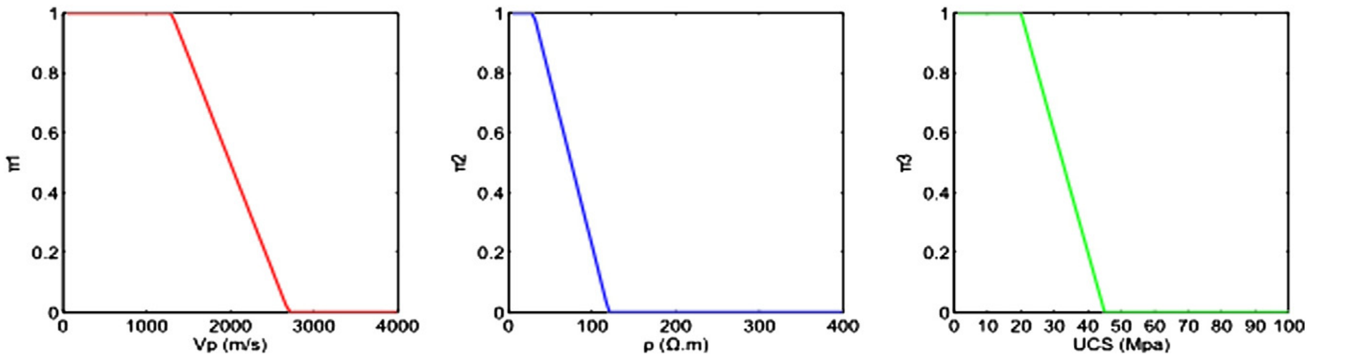

Fig. 4. The three belonging functions used for geophysical parameter fusion: π1, π2 and π3 respectively show the possibility of the medium being i) fissured, ii) saturated with water, and iii) unconfined, according to the Vp, Vs and ρ.

– **Hypothesis h_2** assumes that the soil strata are saturated with water: its possibility π_2 is correlated with the observed resistivity values. From our geomorphological knowledge of the landslide and from field observations, the soil strata is saturated if the electrical resistivity ρ is less than 10 Ω.m and non-saturated if the electrical resistivity ρ is more than 100 Ω.m. The possibility is assumed to be linear between these two values.
– **Hypothesis h_3** assumes that the soil materials have little strength and are highly weathered: its possibility π_3 is correlated with the computed unconfined compressive strength models. According to Table 1 (Malet, 2003), the UCS observed for weathered marl is below 45. Thus we can consider that bedrock here would be characterized by a UCS above 45 and that the extremely weak uppermost layer by a UCS below 20. The possibility is assumed to be linear between these two values.

The application of this methodology to the La Valette landslide is dedicated to identifying material susceptible to be mobilized within the upper layers of the slide, and particularly between the uppermost sliding layer and underlying bedrock layer. The possibility function Π for such layers is assumed to be high for fractured, water-saturated and very weak materials; it is computed in the cross-section plane (x, z) by Eq. (5):

$$\Pi = \pi_1^* \oplus \pi_2^* \oplus \pi_3^* \tag{5}$$

with

$$\pi^*(X) = \pi(X) \cup (0.5 - L(X)), X = x, z \tag{6}$$

and

$$\pi_i^*(X) \oplus \pi_j^*(X) = \frac{\pi_i^*(X) \wedge \pi_j^*(X)}{sup\left(\pi_i^*(X) \wedge \pi_j^*(X)\right)}, i, j = 1, 2, 3 \tag{7}$$

where the ∧ and ∪ operators stand respectively for the min() and max() function between two values. The expression symbol A⊕B denotes the fusion operator maximum between two functions. L(X) refers to the likelihood values featuring inverted Vp and ρ parameters and estimates from inversion processes (Grandjean et al., 2007). L values were integrated in the fusion process according to Eq. (6), except for the h_3 case that depends on both Vp and Vs likelihoods:

$$\pi_3^*(X) = \pi_3(X) \cup \left(0.5 - L_{Vp}(X)\right) \cup (0.5 - L_{Vs}(X)), X = x, z. \tag{8}$$

The model interpreted from each tomogram (Figure 3) and the model constructed by the methodology proposed here (Figure 5) show a lot of similarities. The sliding plane is more visible on the fusion model than on separate tomograms and the stable area defined in Fig. 3 from boreholes and surface observations is well recognized in Fig. 5 as the crest separating the two soft domains of the surficial layer. This surficial layer corresponds to possibility values of between 0.5 and 1.0, while the deeper layer has possibility values of between 0.3 and 0.5. The surficial layer has also a variable thickness ranging from 0 m near the flanks to 10–15 m over the body of the landslide. This was confirmed by data from the boreholes drilled close to the section that indicate a slight discrepancy between the depth to the bottom of the weathered layer as deduced from the fusion and that measured in the borehole. From this point of view, the accuracy of the proposed method can be evaluated as being within a few meters, which is not trivial.

In particular, the reliability of the resulting possibility section depends on several components such as a) the resolution at which geophysical measurements are carried out and processed to produce

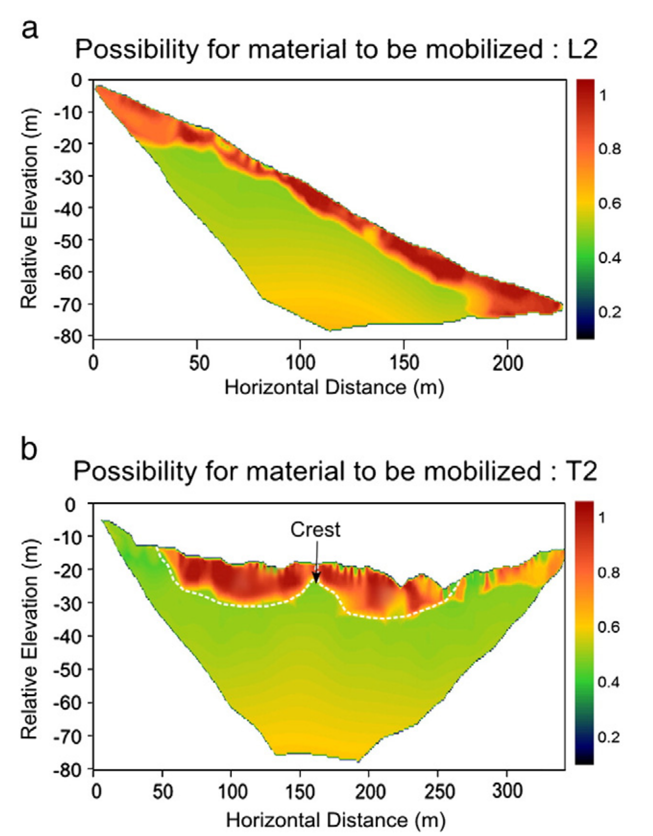

Fig. 5. Resulting sections (a: Profile L2 and b: Profile T2) indicating the possibility of material being mobilized during erosion and sliding. The 0.5 possibility value on these images represents the limit between reworkable material and bedrock. For boreholes B1 and B2b, black = weathered marl, shaded = sound marl.

the parameter grids, b) the uncertainties inherent in the inversion schemes and materialized by the likelihood values, and c) the accuracy of the belonging functions, i.e. the values defining the limits of the conditions $\pi = 1$ or $\pi = 0$. These three aspects can nevertheless be improved to ensure maximum quality for the final sections.

Where the first point is concerned, the measurement protocols (measurement spacing, depth of signal penetration, etc.) for each geophysical method considered in the fusion process must be in good agreement with the size and distribution of the soil anomalies to be imaged. The inversion grids for the seismic and geoelectric tomograms should at least respect the same discretizing conditions.

The second point relates to the distribution of the likelihood values. These should be as high as possible over the whole of each tomogram, indicating that the inversion process has successfully found the inverted parameters with minimum errors. Optimizing such processes requires the inverse problem to be well posed so that a) the parameters to be inverted can explain the information contained in the data, and b) the spatial density of the measurements authorizes a large part of the section to be sounded.

The last point refers to the definition of the belonging function. Because this issue directly impacts the fusion results, the limiting values need to be selected carefully. The choice in this study was to use surface observations and compare them to the tomogram values. This approach can be significantly improved by using in situ measurements from part of the section in order to calibrate the belonging functions. Unfortunately, as in the present case, such data are not always available in the vicinity of the studied section.

The proposed fusion process thus has potential for characterizing complex structures, such as landslides, from geophysical data. It is a characterization that gives a kind of realization level to the hydro-geomechanical hypothesis when few quantitative data are available. As Grandjean et al. (2007) point out, the data fusion approach allows the geophysical methods to provide more constrained information than when they are considered separately. The use of belonging functions provides the expert with the possibility of adjusting the boundaries of each hypothesis according to the knowledge he may have of the studied area. Nevertheless, the method is directly dependent on the quality of both the geophysical data and the inversion process. Even though this approach cannot replace more traditional studies based on the correlation between geophysical sections and laboratory measurements, it can produce a reliable coherent model with less laboratory work.

3. Conclusion

A combined geophysical approach based on seismic and electrical measurements was conducted on the La Valette landslide in order to determine its geomorphological structure. The P-wave velocity (Vp) and S-wave velocity (Vs) provide information on the layer's compaction state and the material's porosity, while the electrical resistivity (ρ) provides an important indication concerning variations in the material's water content. Geophysical tomograms were computed from the geophysical data and interpreted using the "fuzzy set" theory to determine the potentially remobilizable layers of the landslide. Once the geophysical quantities had been identified, a fusion strategy was adopted via three belonging functions defining the possibility of a physical phenomenon and correlating directly with a geophysical parameter. The fusion process uses geotechnical empirical relationships to assess the weakness state of the landslide layers. Due, however, to the lack of knowledge about the mechanical properties of the studied La Valette materials, we used generic properties correlated against available data from neighboring sites. This is certainly a limitation as regards the study, and of the future prospects of the work will be to determine the geotechnical properties at various places of the La Valetta site. Following the fusion process, taking into account likelihood distributions derived from the inversion processes, two sections were proposed for interpretation; these highlight places in the subsurface where the rocks may be subjected to reworking or sliding due to rain and water infiltration. As these zones were successfully correlated against two boreholes put down on profile T2, we consider that the method has been validated for the La Valette site and is promising for similar studies in the future.

Acknowledgments

This study, made possible through collaboration between BRGM and IPG (Strasbourg), was financially supported by BRGM and the French ANR Ecoupref project. We would like to express our gratitude to the experiment's participants, without whom the study would not have been possible, and we would also like thank the reviewers for their helpful comments and recommendations.

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