Geophysical data fusion applied to the characterization of the La Valette mudslide

Gilles Grandjean
French Geological Survey

Adnand Bitri
French Geological Survey

Julien Travelletti
CSD Ingénieurs SA

Geophysical data fusion applied to the characterization of the La Valette landslide

G. Grandjean, C. Hibert & A. Bitri
BRGM, Planning service and natural hazards, Orléans, France

J. Travelletti & J.-P. Malet
CNRS UMR 7516, School and Observatory of Earth Sciences, University of Strasbourg, Strasbourg, France

ABSTRACT: Geophysical methods such as seismic surveying or electrical resistivity imaging appear to be well-adapted to investigate landslide's structures and understand related mechanisms. These methods allow direct and non-intrusive measurements of acoustic (P), shear (S) wave velocity and electrical resistivity, three physical parameters considered as essential to estimate mechanical properties of reworked moving materials. Both of these methods were applied on the La Valette landslide, in the French South Alps, where a typical example of intra-material mudslide can be observed. Measurements were taken simultaneously along 2 profiles of 400 m and 300 m in length, respectively perpendicularly to and along the axis of the mudslide. The P and S-wave velocity fields, as well as the electrical resistivity field, were inverted from recorded data according to suitable algorithms. P and S-wave velocity images as well as resistivity tomographies are presented as results and discussed in term of reliability. Preliminary interpreted results show a correlation between the seismic velocities and electrical resistivity data, confirming that the simultaneous use of both methods gives complementary information on geomechanical behaviour of the landslide. Seismic data provide information on fissure density variations and the presence of shear-bent material, whereas the electrical resistivity ones provide information on water content variations. In order to go deeper into petrophysical interpretation, a data fusion strategy based on fuzzy subsets theory is developed and applied to the geophysical dataset. The resulting cross-sections show the possibility of geomechanical hypotheses to be realized in specific areas of the tomographic cross-section, highlighting the places where sediment mobilization could occur.

1 INTRODUCTION

French Alps are affected by numerous active landslides, particularly in clay-shale deposits (Malet, 2003). These unstable areas are characterized either by movements occurring along discrete shearing surface (Brunsden & Ibsen, 1993; Hungr et al., 2001) or by continuous deformations depending on local constraints, slope gradient and subsurface material properties (Baum et al., 1998). They are generally composed of heterogeneous clay-rich clastic materials, nearly saturated in water during the wet seasons.

The objective of this work is to propose an original method for characterizing the geometry of subsurface clay-rich materials susceptible to be eroded by analyzing and combining several geophysical parameters by the mean of the Fuzzy Set theory. Non-intrusive geophysical methods such as seismic refraction and electrical resistivity imaging are well adapted for studying the mechanical behavior of landslides. The combined interpretations of seismic travel times and electrical apparent resitivities can reveal the mechanical and hydrological properties of a terrain sub-surface. Three physicals quantities are here considered: the acoustic P-wave velocity (Vp) providing information on the fissuration state of the soil matrix; the electrical resistivity (ρ) giving indications on the water saturation of the porous media and S-wave velocity (Vs) providing information on soil stiffness when Spectral analysis of Surface Waves (SASW) is used.

According to previous studies (Reynolds et al., 2002; Cutlac, 2005; Grandjean et al., 2007; Godio et al., 2003) a multi-method approach is proposed to increase the level of information. Grandjean and al. (2006) have studied the correlation between Vp and ρ on the active Super-Sauze mudslide. This work showed that a cross-plot between inverted Vp and ρ values help distinguishing between several soil characteristics. Referring to field observations, Grandjean and al. (2007) demonstrated also that one type of behavior was related to the amount of soil porosity controlled by cracking and fracturing, and that another type was related to the water saturation state of the porous medium.

Indeed, the increase in the Vp and ρ values appeared to be related to a decrease in porosity and an increase in water content with depth (Grandjean et al., 2006. These results led to propose a new quantitative method able to reveal different geomechanical behaviors by using the Fuzzy Set theory to merge several geophysical parameters. Already used in Grandjean et al. (2007), this methodology produced so encouraging results that we decided to test it on the La Valette site.

The La Valette landslide (Fig. 1) is located in the Ubaye valley (Alpes-de-Haute-Provence, France). The basin has characteristic badlands morphology with multiple V-shape gullies incised by erosion and flank slopes varying from 30° to 70°. The landslide has developed in black marls, known as “Terres Noires”, with shades varying from black to grey (Antoine, et al., 1995).

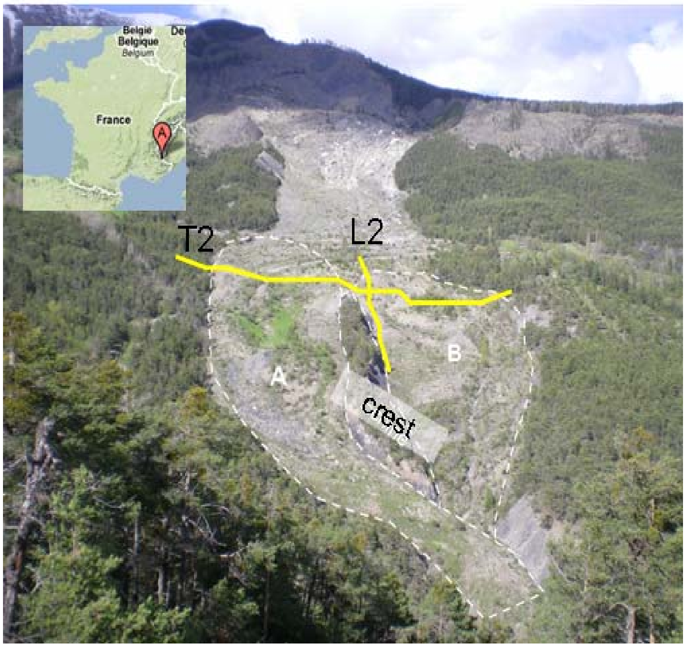

Figure 1. Location map and general view of the La Valette landslide. The two geophysical profiles (T2: transverse; L2: longitudinal) are shown in yellow; in the bottom part, the landslide shares into A and B.

2 GEOPHYSICAL EXPERIMENTS

The geophysical prospection was done using seismic and electrical systems spread along the 400 and 300 meters of T2 and L2 profiles respectively.

2.1 *Seismic P-wave tomography*

The acquisition system involved 48 channels seismic equipment featured by 10 Hz geophones and a handy-hammer source. Geophones were set every 5 meters; seismic shots were done every 15 meters. Data processing and inversion of the first arrival travel times were undertaken using the JaTS seismic tomography software Grandjean and Sage (2004). Figure 2a and 2b shows the P-wave velocity (Vp) distribution along the T2 and L2 profiles, respectively.

2.2 *Spectral analysis of surface waves (SASW)*

SASW is of increasing interest in the geophysical community (Yaramanci, 2004) because it offers a non-invasive means of evaluating soil shear modulus with depth (O’Neill et al., 2003). This method can be easily implemented along linear sections to obtain a two-dimensional shear-wave velocity profile of shallow layers (Miller et al., 1999). Before the inversion step, 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, dispersion images have to be computed in a more local manner with respect to the 1D assumption required by the Levenberg-Marquardt inversion method proposed by Herrmann (2002). To tackle this problem, the 2M-SASW technique (Multifold Multichannel SASW; Grandjean and Bitri, 2007) has been used on the same seismic data used previously for P-wave tomography. To obtain a 2D section, the 1D shear-wave velocity profiles inverted for each local dispersion curves were interpolated along the seismic line using a krigging algorithm. Reliability of inverted Vs profiles are directly given by the diagonal values of the correlation matrix. Figure 2c and 2d shows the S-wave velocity (Vs) distribution along the T2 and L2 profiles respectively.

2.3 *Electrical resistivity tomography*

The electrical apparent resistivity profile was acquired along the seismic profile, using a Wenner-Schlumberger array. Electrodes were distant of about 5 meters each others. Data processing and inversion were carried out according to Loke (1994) implementing a damped least-squared Gauss-Newton algorithm. Figure 2e and 2f shows the electrical resistivity (ρ) distribution along the T2 and L2 profiles respectively.

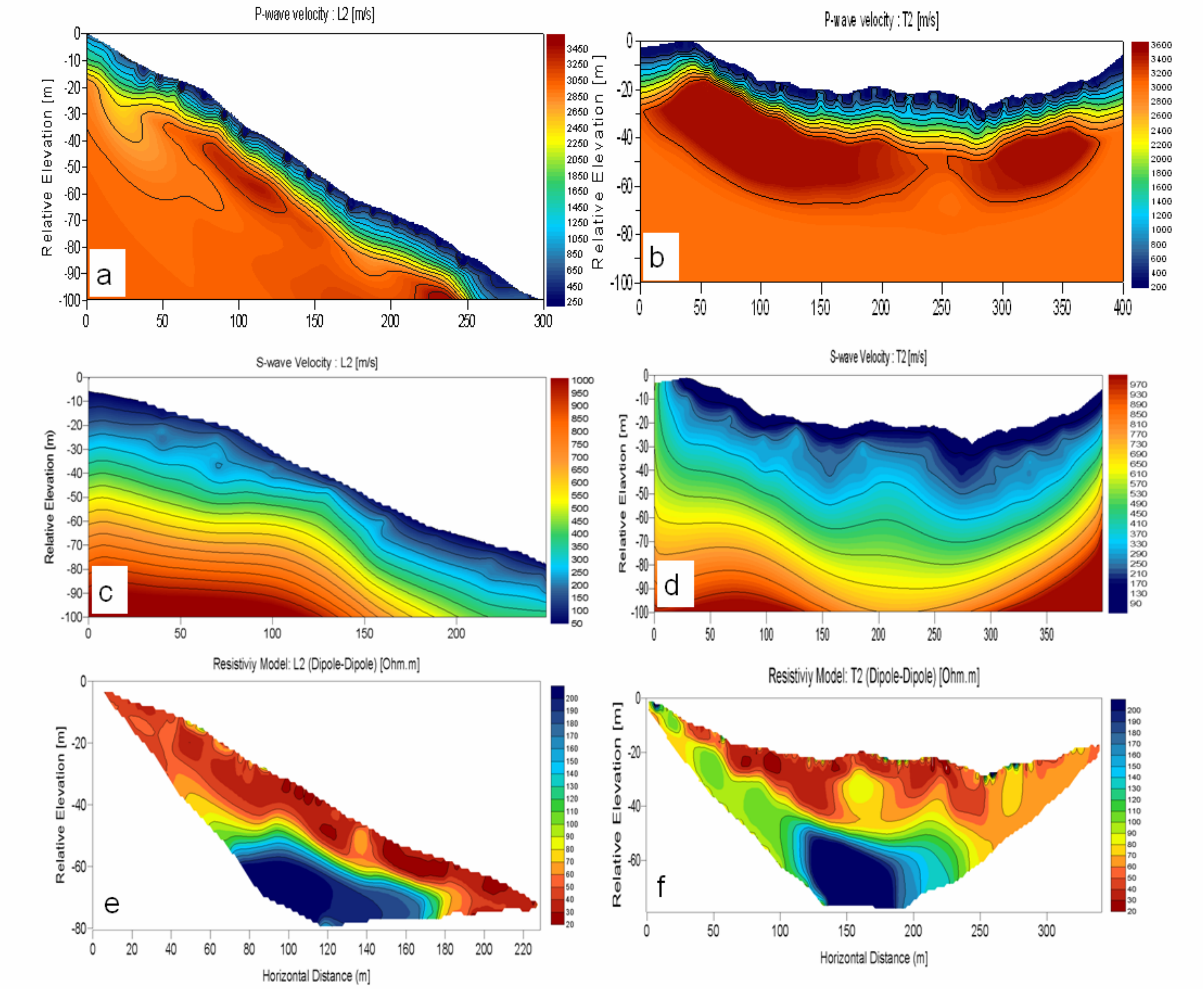

Figure 2. 2D Geophysical images along profiles T2 (b;d;f)) and L2 (a;c;e), for.P-waves velocities (a;b), S-waves velocities (c;d) and electrical resistivities (e;f).

3 GEOPHYSICAL DATA FUSION

Interpreting geophysical data for geological or geotechnical applications raises important issues related to uncertainties inherent to measuring and processing steps. Fortunately, different mathematical tools allow data imperfection to be considered such as the probability, evidence and possibility theories. In this paper, probability theory is supposed to be known to analyze geophysical data. Therefore, only the basics of the possibility theory are exposed as a new approach to manipulate the uncertainty related to geological and geomechanical interpretations. The possibility theory has been introduced by Zadeh (1965) and presented by Dubois and Prade (1980). Fully described in Grandjean et al. (2007), we present here the different hypotheses formalized by the belonging functions. On the basis of geomorphological observations and according to the tomographies computed in the previous sections, some soil outcrops were describes from a hydro-mechanical point of view. These macro descriptions were then used to express three hypotheses referring to the possibility functions (ranging from 0 to 1) expressed by:

- Hypothesis *h1* defines the possibility $\pi 1$ of the soil strata to be densely affected by cracking due to the traction forces occurring during sliding. The density of cracking is correlated with the variation of the P-wave velocity observed at the subsurface. From the geomorphological knowledge of the mudslide, the soil strata is respectively fissured and not fissured if the P-waves velocity is lower than 300 m.s^{-1} and greater than 1500 m.s^{-1}. The possibility is assumed to be linear between these two values;
- Hypothesis *h2* defines the possibility $\pi 2$ of the soil strata to be saturated in water according to the observed values resistivity. From the geomorphological knowledge of the mudslide and from field observations, the soil strata is respectively saturated and not saturated if the electrical resistivity ρ is lower than 10 Ω.m and greater than 100

Ω.m. The possibility is assumed to be linear between these two values;

- Hypothesis *h3* defines the possibility *π3* of the soil strata to have relatively low unconfined compression strength (Es) depending on the Vs/Vs ratio.

The last information being integrated concern the likelihood functions. Nifle and Reynaud (2000) demonstrated that data fusion between possibility and probability functions has a mathematical sense only in the framework of evidence theory. In our case, each possibility function *π1 π2* or *π3* is combined with likelihood functions L(x)*1,* L(x)*2* or L(x)*3* that refer to the distributions of the likelihood values computed during each inversion process.

4 APPLICATION TO THE LA VALETTE SITE

The application of this methodology on the La Valette landslide was dedicated to identify materials susceptible to be mobilized within the landslide. The strategy consisted to compute a fusion model for the two studied sections combining Vp, ρ, and Es. The fusion of hypothesis *h1*, *h2* and *h3* was then implemented by using a fusion operator described in Grandjean et al. (2007) and combining *π1, π2, π3* with L(x)*1,* L(x)*2,* L(x)*3.*

Figure 3 shows the result of this fusion for the two profiles L2 and T2. The possibility model shown in this figure reveals a surficial layer with a possibility value between 0.5 and 1.0 under which a layer with lower possibilities values ranging from 0.3 to 0.5 can be observed. Validated by borehole observations, the surficial layer has a variable thickness ranging from 0 m near the flanks of the landslide to 10-15 m over the landslide.

The surficial layer may be interpreted as the part of the landslide able to be reworked during crisis periods; the lower layer being considered as the bedrock, unable to be affected. Along the transverse section T2, we can easily identify the two parts of the landslide A and B appearing as low possibility areas. Between them, we can recognize the buried crest formed by an outcrop of the autochthonous materials (Fig.3b). This interpretation was rather difficult to carry out on individual geophysical tomograms of Figure 2, since the characterization of these structures is strongly depending on several physical properties. The proposed fusion process thus demonstrates its potentiality in the hydro-geomechanical characterization of complex structures like landslides from geophysical data.

5 CONCLUSION

A combined geophysical approach based on seismic and electrical measurements has been conducted on the La Valette landslide in order to determine the geomorphological structure. The interpretation of P-wave velocity (Vp) and S-wave velocity (Vs) provides information on the state of compaction of the layer and on the porosity of the material. The electrical resistivity (ρ) gives important indications on the water content variations. Geophysical tomograms were computed from geophysical data and interpreted using Fuzzy Set theory to recognize the layers potentially reworkable of the mudslide.

ACKNOWLEDGMENTS

This work was realized thanks to collaboration between BRGM, IPG of Strasbourg and with the support of the French national ANR project ECOU-PREF.

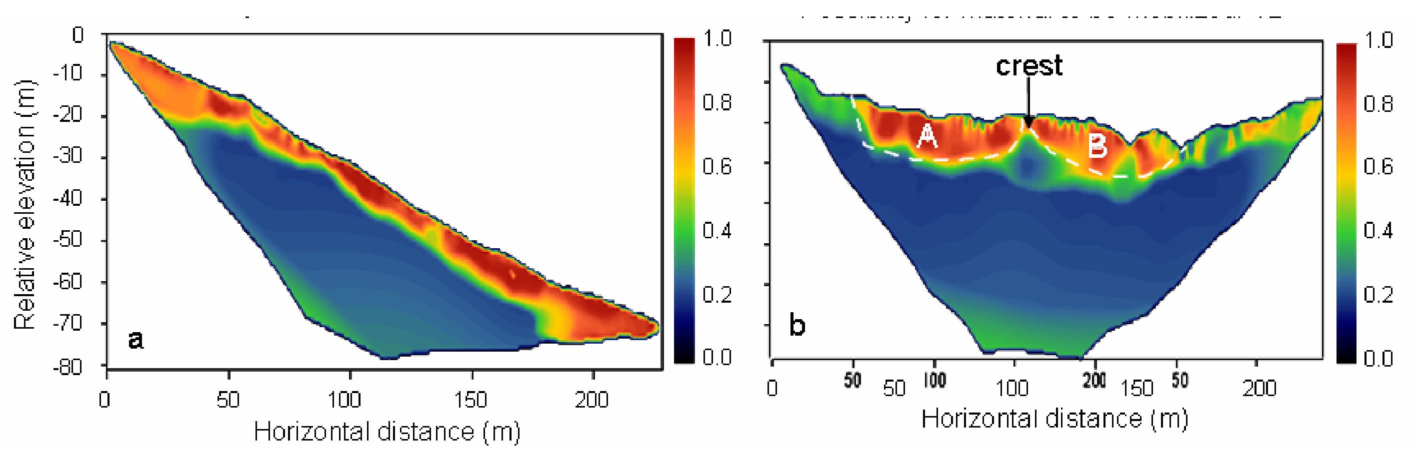

Figure 3. Resulting sections (a: Profile L2 and b: Profile T2) indicating the possibility for materials to be mobilized during erosion and sliding processes.On these images, the 0.5 value of possibility represents the limit between reworkable materials and the bedrock.

REFERENCES

Antoine P., Giraud A., Meunier M., van Asch Th.W.J. 1995. Geological and geotechnical of the "Terres Noires" in southeastern France: Weathering, erosion, solid transport and instability..Engineering Geology, 40, 223-234.

Baum R.L., Messerich J., Fleming R.W. 1998. Surface deformation of slow-moing, clay-rich landslides, Honolulu Hawaii. Env. Eng. Geoscience, 4, 283-306.

Brunsden D., Ibsen M.-L. 1996. Mudslide. In: landslide recognition: identification, movement and causes. Wiley, Chichester, United Kingdom, 103-119.

Cutlac O. 2005. Multi-method geophysical surveys for the study of Holocene landslide deposits. In: Proc. EGS-AGU-EUG Joint Assembly, New Orleans, USA. Ext. Abstr. NS23B-08.

Dubois D., Prade H. 1980. Fuzzy sets and systems: theory and applications. – Academic press, New York, 224 p.

Godio A., De Bacco G. and Strobbia C. 2003. Geophysical characterisation of a rockslide in an alpine region. Proc. EGS-AGU-EUG Joint Assembly, Nice, Farnce, Vol. 5, 12480.

Grandjean G. and Sage S. 2004. JaTS: a fully portable seismic tomography software based on Fresnel wavepaths and a probabilistic reconstruction approach. Comp. & Geosciences, 30, 925-935.

Grandjean G., Bitri A., Pennetier C., Méric O., Malet J.-P. 2006. Caractérisation de la structure interne et de l'état hydrique de glissements argilo-marneux par tomographie géophysique : l'expemple du terrain de Super-Sauze. C. R. Acad. Sci.. 338, 587-595

Grandjean G., Bitri A. 2007. 2M-SASW: multifold multichannels seismic inversion of local dispersion of Rayleigh wave in laterally heterogeneous subsurfaces: application to the Super-Sauze mudslide (France). Near Surf. Geophys., 30, 925-935.

Grandjean G., Malet J.-P., Bitri A., Méric O. 2007. Geophysical data fusion by fuzzylogic for imaging the mechanical behaviour of mudslides. Bull. Soc. Géol. Fr., 2, 127-136.

Herrmann R.B. 2002. Computer programs in seismology. Department of Earth and Atmospheric Sciences, Saint Louis University, USA.

Hungr O., Evans S.G., Bovis M.J. and Hutchinson J.N. 2001 A review of the classification of landslides of the flow type. Environ. Eng. Geoscience, 7, 221-238.

Loke M.H. 1994. The inversion of two dimensional resistivity data. PhD Thesis, Univ. of Birmingham, Birmingham, UK, 122p.

Malet J.-P. 2003. Les "glissements de type écoulement" dans les marnes noires des Alpes du sud. Morphologie, fonctionnement et modélisation hydro-mécanique. Thèse de Doctorat, Univ. Louis Pasteur, Strasbourg I, France, 394 p.

Miller R.D., Xia J., Park C.B., Ivanov J. 1999. Multichannel analysis of surfaces waves to map bedrock. Leading Edge, 18, 1392-1396.

Nifle A., Reynaud R. 2000. Double representation of information and hybrid combination for identification systems. Proc. 3rd Int. Conf. on Information Fusion, Paris France, Vol.1, 23-30.

O'Neill A., Dentith M., List R. 2003. Full-waveform P-SV reflectivity inversion of surface waves for shallow engineering application. Expl. Geophys., 34, 158-173.

Park C.B., Miller R.D., Xia J. 1998. Imaging dispersion curves of surface waves on multi-channel record. – SEG Ext. Abstr., New Orleans, USA, SEG Ed., 1377-1380.

Reynolds J.M. 2002. Application of geophysics to landslide investigations. In: Landslides and landslide management in North Walles. – the national Museum and Galleries of Wales, Cardiff, 28-30.

Yaramanci U. 2004. Seismic surface waves in near surface geophysics. First Break, Nov. 2004, 4-6.

Zadeh L.A. 1965. Fuzzy sets. Inform. And Control, 8, 338-353.