Integration of geomorphological, geophysical and geotechnical data to define the 3D morpho-structure of the La Valette mudslide, Ubaye Valley, French Alps

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ABSTRACT: In order to define and characterize the 3D morpho-structure and the volume of the lower part of the La Valette mudslide (Alpes-de-Haute-Provence, France), a methodology based on the integration of multi-source data is proposed. The information on the structure is derived: (i) from a geomorphological analysis of the landscape (IGN aerial photographs, digital elevation model, field survey), (ii) from geotechnical parameters obtained from several boreholes and inclinometers measurements, (iii) from the lateral and vertical variations of geophysical parameters (resistivity ρ, seismic velocity Vp and Vs). A method to integrate the information in a geological modeller is detailed.

1 INTRODUCTION

The characterization of the structure of a landslide is a prerequisite for defining the volume of the moving mass and analysing its behaviour. Very often, the structure is defined according to the variation of some few sensitive parameters which have to be carefully chosen according to the geological and hydrogeological setting of the landslide (Jongmans & Garambois, 2007). For landslides developed in black marls, several authors indicated that relevant geophysical parameters are the electric resistivity ρ of the subsoil and the seismic velocity Vp and Vs (Grandjean et al., 2007; Méric et al., 2007), and that relevant geotechnical parameters are the pressiometric modulus (E_M) and the pressure limit (P_L) which defines respectively the pseudo-elastic behaviour of the soil and the soil resistance to failure (Flageollet et al., 2000). Information on the structure and the topography covered by the moving mass can also be obtained from detailed geomorphological and geological analyses, by combining the interpretation of old photographs, maps, digital elevations models, and field surveys. Some of these parameters are acquired at specific points, others are directly acquired along cross-sections, and others are already in 3D like the DEMs.

Major difficulties in interpreting and integrating this multi-source data are therefore the accuracy of the measure of the parameters, their spatial variability and the upscaling of the punctual information to a spatial information. The objective of this work is therefore to present a methodology to integrate this multi-source information in a geological modeller in order to create a realistic computerized representation (eg. 3D grids) of the landslide volume and structure as an input for geomechanical modelling and hazard analyses. The aim is to integrate information from DEMs, from surface geomorphological boundaries, from geophysical interpreted cross-sections, and from downhole boreholde data.

The methodology has been developed on the La Valette mudslide, triggered in March 1982 and which is one of the most important slope instabilities in the South French Alps. The dimensions of the mudslide are respectively a length of 1380 m, a width of 290 m, an estimated volume of 3.5 10^6 m^3, and an average slope gradient of 18°. Velocities lie in the range from 0.05-0.40 $m.day^{-1}$. The mudslide affects a hillslope located over the municipality of St-Pons, and is a potential threat for the 170 community housings located downstream (Le Mignon & Cojean, 2002). From a geological viewpoint, the landslide has developed in allochtoneous flysch and calcareous sandstones of the Autapie sheetrust and in Callovo-Oxfordian autochtonous black marls (Fig.1); from a geomorphological viewpoint, it has progressively filled parts of the thalwegs of two adjacent torrents (Serres and La Valette torrents). A detailed description of the development of the mudslide can be found in van Beek and van Asch (1996) and Squarzoni et al. (2005). Since 2002, an important activity of the main scarp is noticed with a retrogression of several meters associated to rotational failures. The failed material is currently charging the upper part of the mudslide, is progressively moving downstream and accumulating in the lower part around a stable crest. Around this stable crest, an elevation of the soil surface and an increase of the slope gradient are observed. Therefore, this area is of particular interest in order to analyse the possibility of potential fluidization of the moving mass in a rapid mudflow (LeMignon & Cojean, 2002).

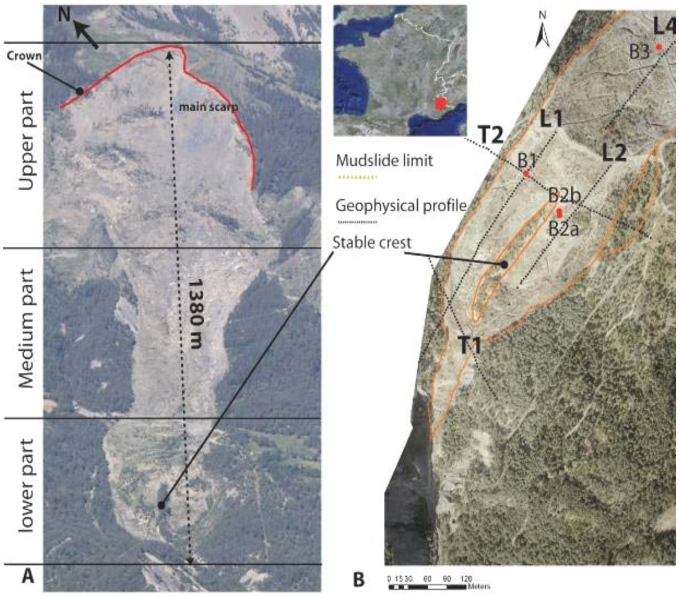

Figure 1. La Valette mudslide: A) General view; B) Orthophotograph (2007) of the lower part and location of the geophysical cross-sections and the boreholes around the stable crest.

2 METHODOLOGY

A multidisciplinary approach based on geomorphological analysis, geophysical and geotechnical investigations was carried out.

2.1 Geomorphological analysis

The localization of the limits of the mudslide, the stable crest and the two adjacent thalwegs of the Serre and La Valette torrents were extracted from a serie of IGN photographs from 1974 until 2007. Digital elevation models (DEM) were also used to precisely identify the stable slopes from the moving mass. This analysis was completed by field observations.

2.2 Geophysical investigations

The geophysical investigation included two transverse profiles approximately perpendicular to the main sliding direction (T1, T2) and three longitudinal profiles in the direction of the displacements (L1, L2, L4) (Fig.1). For the profiles T1 and T2, the topographical conditions have allowed to carry out geophysical measurements on the stable hillslopes bordering the mudslide to characterize the moving mass both in the lateral and vertical directions.

The Electrical Resistivity Tomography (ERT) survey is composed of 5 m-interval electrodes spacing along a distance of 235 m to 415 m depending on the number of electrodes (48 to 84 electrodes). A Wenner-Schumberger configuration was selected because of its good signal to noise ratio property and its good compromise to detect both horizontal and vertical contrasts. Acquisitions with a Dipole-Dipole configuration were also performed because of larger theoretical resolution in sub-surface with a larger number of collected data. The ERT profiles were coupled to seismic acquisitions to better constrain the interpretation (Vp and Vs tomographies using a 5 m-interval between the geophones and 15 m-interval shots). The surface waves were recorded during seismic refraction acquisitions.

Processing of the ERT data was carried out according to Loke (1994) implementing a damped least-squared Gauss-Newton algorithm in the Res2DInv software. For the seismic data, the processing of the first arrival travel time waves was carried out with the JaTS seismic tomography software based on the Fresnel volumes for computing wave paths (Hibert, 2008; Grandjean and Sage, 2004). The inversion of the S-wave was realized with the SIRayD software based on the SURF algorithm (Hermann, 1984) that allows to calculate the dispersion curve and to obtain a S-wave vertical velocity profile by 1D inversion (Socco & Jongmans, 2004). To obtain a 2D section, the 1D S-wave velocity profiles inverted from each local dispersion curves were interpolated along the seismic profiles.

In order to represent the profile in 3D, the geometry was simplified with an orthogonal projection on a linear regression line. Finally the 2D coordinates were converted into 3D geographical coordinates.

2.3 Geotechnical investigations

Four destructive boreholes B1, B2a, B2b and B3 were realized until the depths of -30 to -40 m in July 2008, close to the geophysical profiles (Fig. 1). Geotechnical tests were further performed in the drilling at relevant depths in the mudslide body and in the stable bedrock, such as pressiometric tests (to characterize in-situ the pressiometric modulus -E_M- and the pressure limit -P_{L}-) and Lugeon high pressure permeability tests. An inclinometer casing has been installed in borehole B3 for weekly deformation measurements, and 3 piezometric tubes have been installed in the other boreholes.

3 GEOTECHNICAL MODELS

The internal structure of the lower part of the mudslide does not present important lithological variations until the top of the marl bedrock located respectively at -20.7m, -16.5m, -17.2m and -25.0m in the boreholes B1, B2a, B2b and B3 respectively. The mudslide body is composed of more or less coarse marly clayey material with variable degree of compaction (Fig. 2a).

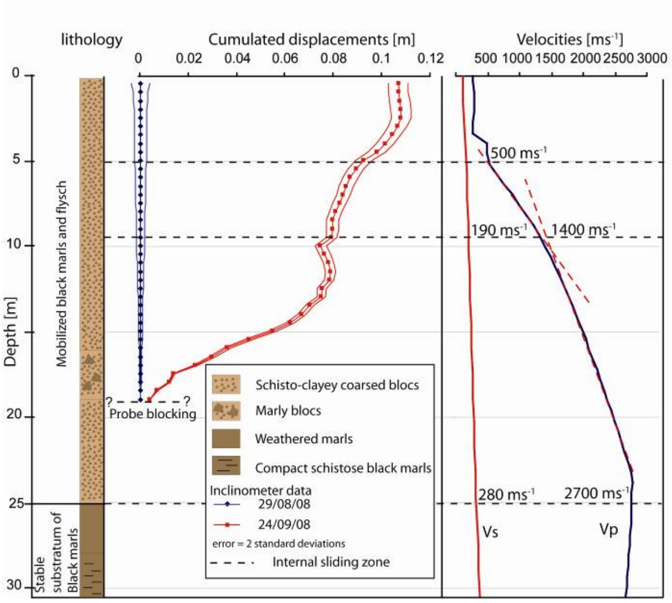

Figure 2. a) Internal structure of the La Valette mudslide at location of borehole B3: geotechnical log and vertical profile of the cumulated displacements from inclinometer data. The cumulated displacements start at -9 m because of the blocking of the probe at this depth during the initial reference measurement. b) Vertical profile of Vp and Vs velocities Inverted from the tomography.

Analysis of the deformation of borehole B3 between September and October 2008 tends to indicate the possibility of several internal sliding surfaces in the shallow unit of the mobilized mass (at -5m and -10m) and a nearly visco-plastic behaviour underneath with a decrease of the shear rate with the depth (Fig. 2a). A sliding surface is also identified at the contact between the bedrock and the mobilized mass. This vertical structure including an internal slip surface separating the topmost active unit from the lowermost stable unit was also identified in the Super Sauze mudslide developed in the same geological setting (Malet & Maquaire, 2003). The internal structure from the borehole B3 can be summarized with:

- a shallow unit, about 10m thick, composed of mobilized black marls and flyschs in a heterogenous sandy silty matrix. Ranges of geotechnical parameter values (pressiometric modulus E_M from 6-18 Mpa; pressure limit P_L from 0.5-1.0 Mpa) are defined.
- a deeper unit, localized at -10m deep for a thickness of about 15m. Ranges of geotechnical parameters are similar to those of the shallow unit.
- The bedrock composed of consolidated black marls, localized at -25m in average. The values of hydrological and geotechnical parameters are within the range of 10^{-7}-10^{-8} m.s^{-1} for the permeability, 228-720 Mpa for the pressiometric modulus E_M, and P_L > 8 Mpa for the pressure limit .

4 GEOPHYSICAL MODELS

Results of the electrical (RMS errors lower than 2%) and seismic tomography indicate a good contrast in ρ resistivity and Vp velocities between the moving mass and the bedrock of black marls (Fig. 3). To determine the depths where the data are still relevant, the Depth of Investigation (DOI) method described in Marescot and Loke (2004) was applied to the inverted resistivity values. The calculations of the DOI index show that it is not possible to get reliable interpretations under the transition of the mobilized mass and the stable substratum where the resistivity contrast is the most important. Concerning the Vp topographies, the reliability of the inversed velocities is based on the Fresnel wavepaths density (Grandjean and Sage, 2004). The investigation depth is about 30m in the centre of the profiles and decreases rapidly towards the lateral boundary of the model.

A three-layer scheme is identified from the parameters Vp, Vs and ρ (Table 1). This structure, as well as the range of geophysical property values, is similar to those observed in other mudslides developed in black marls (Schmutz et al., 2000; Méric et al., 2007; Grandjean et al., 2007). The vertical profile of Vp velocity in boreholes B3 seems also to correspond to the three-layer stratification observed in the vertical profile of cumulated displacements from inclinometer data. (Fig. 3b).

Table 1. Geophysical parameter value for the three layers. The layers 1-2 correspond to the moving mass and the layer 3 corresponds to the bedrock.

	Vp	Vs	ρ
	m.s^{-1}	m.s^{-1}	ohm.m
Layer 1	240 to 1400	70 to 180	5 to 50
Layer 2	1400 to 2700	180 to 260	50 to 100
Layer 3	2700 to 3500	> 260	> 100

The depth of bedrock derived from the electrical and seismical tomographies are validated by the geotechnical data of the boreholes and the field observations (Fig. 3a). Therefore, the geophysical model of profile T2 is considered as the reference to interpret the data and to make coherent the tomographies of profiles L1, L2 and T1. Indeed, some geophysical profiles display some discrepancies at their intersection which can be linked to problems of nonuniqueness of the inversion or to lateral variations of resistivity and velocity.

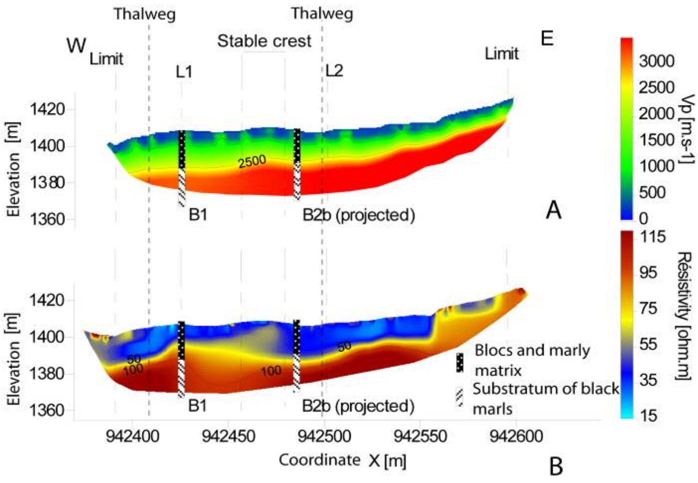

Figure 3. Interpretation of P-wave velocity Vp and resistivity ρ tomography for the profile T2.

According to the sensibility and the investigation depth of each method, the P-wave velocity is mainly used to constrain the interpretation of the strcture in depth, and the resistivity ρ is used to constrain the interpretation laterally and in the subsurface. The S-wave velocity is not considered relevant to characterize the structural pattern, as it does not discriminate vertically the different layers (Fig. 3).

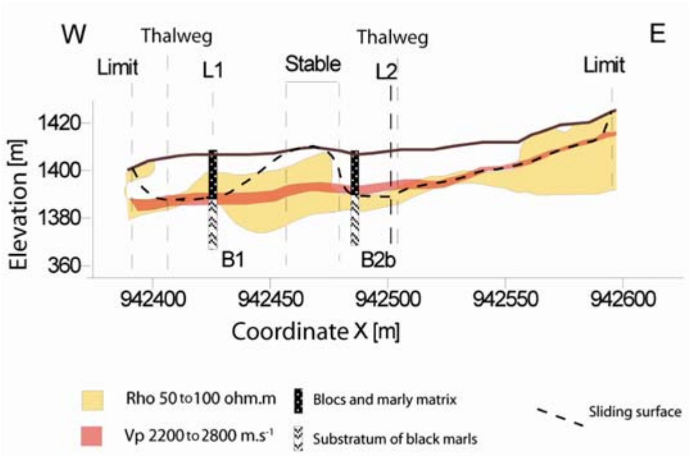

Figure 4. Methodology to define the depth of the bedrock by combining envelopes of parameter values, with example of profile T2.

5 MORPHO-STRUCTURAL MODEL

In the lower part of the mudslide, the paleotopography is characterized by two parallel thalwegs with steep and asymmetrical slopes. Their confluence is located downstream of the stable crest (Fig. 5a). These torrents correspond to low topographical points that are also used to constrain the morpho-structural model (Fig. 4; Fig. 5b, c). Compared to the NE-SW axis of the stable crest, the position of the thalwegs is asymmetrical and is quite well identified by the resistivity tomographies (Fig. 3; Fig. 4).

In order to integrate all the information in the geological modeller (*RockWorks*©), the interpreted structural profiles have been represented into several virtual boreholes with information on the depth and thickness of each layer. The points located within the stable part are represented by a virtual borehole containing only information for layer 3 (bedrock). As a first step in the geostatistical modelling, an inverse distance interpolation method has been used to construct a 3D model.

The volume of the lower part of the mudslide is estimated at 885,000 m^3 (Fig. 5c). This estimation of the amount of material accumulated in the lower part of the mudslide represents ca. one quarter of the total volume of the mudslide.

6 DISCUSSION AND CONCLUSION

The 2D electrical resistivity and velocities tomography sections could extent the information from the geotechnical and geomorphological analyses for providing a valuable and continuous representation of the 3D morpho-structure of the mudslide. The structure of the mudslide can be represented by a three layers model, in agreement with previous studies on mudslides located in similar setting. However, the internal structure remains complex: the presence of several sliding surfaces deduced from the inclinometer data is possible. The calculated volume of the mobilized mass in the lower part represents about 885,000 m^3, one quarter of the total mobilized volume by the mudslide.

More information on the paleotopography is still needed to get a more constrained model, with additional geophysical profiles. Finally this methodology will be applied on the whole mudslide and compared with a topographical method based on the local base level concept (SLBL). This concept is defined as a surface above which material are assumed to be erodible by landsliding and can be determined by using an iterative routine (Burbank & Anderson, 2001; Jaboyedoff et al., 2008).

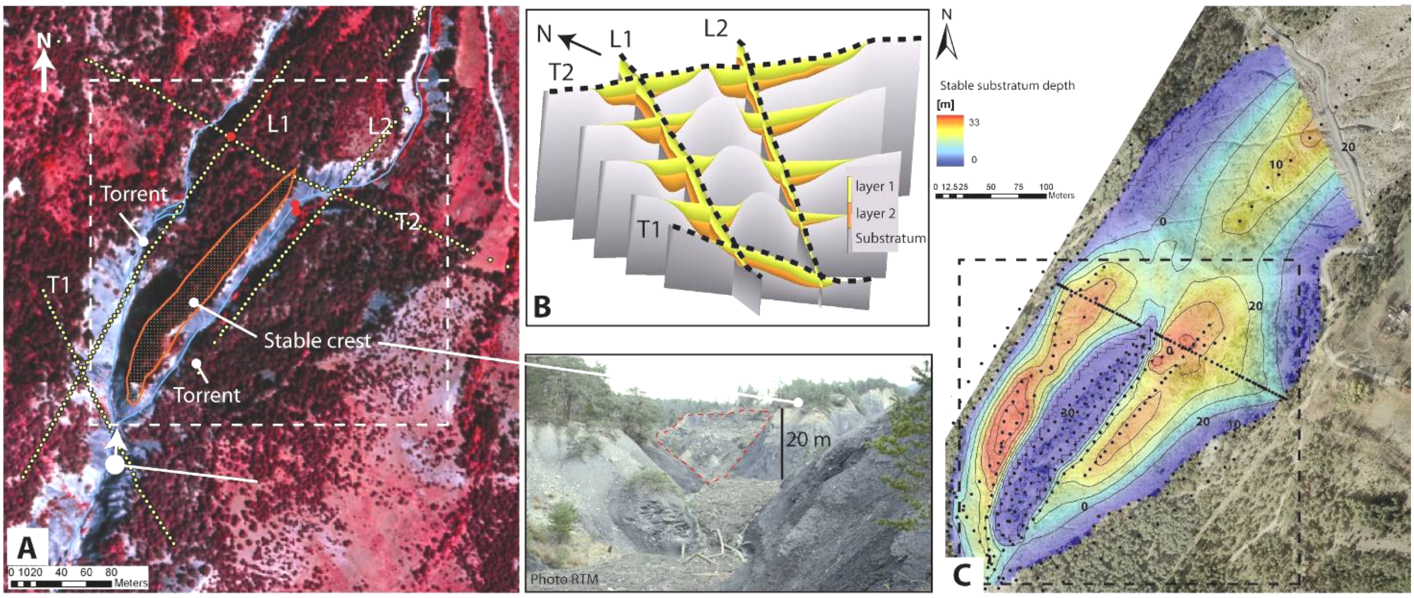

Figure 5. Rebuilding of the lower part topography before the mudslide event. The 1988 RTM picture shows the morphology near the confluence of the thalwegs, the mudslide toe is indicated in red dashed line. A) Orthophotography of 1974 showing the localization of the Serre and La Valette thalwegs around the stable crest, the white dashed area corresponds to the black dashed area in C. B) 3D morpho-structure in three layers (layers 1, 2 and substratum). C) Calculated depth of the sliding surface (top of the stable substratum) in the lower part (orthophotography of 2007). The data used for the layers interpolation are represented by the black dots.

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