



Determination of the 3D structure of an earthflow by geophysical methods The case of Super Sauze, in the French southern Alps

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ABSTRACT

In order to evaluate the risk associated by an earthflow to abruptly evolve into a torrential flow, the knowledge of its internal structure is necessary. Geotechnical methods are important to reach this goal. However, because of the rough topography associated with earthflows, their surface heterogeneities, and the spatial variations of the thickness of the potentially moving mass, non-intrusive geophysical methods offer a very useful tool that complements traditional geotechnical methods. We report the results of a comprehensive study covering a 150 m by 200 m area of the Super Sauze earthflow. This earthflow developed in black marls in the southern French Alps. Shallow electrical conductivity investigations, derived using low frequency domain electromagnetics, maps hidden gullies and crests and lateral variations of the clay and the water content within the first 5 m below the ground surface. Electrical resistivity tomography allows to extrapolate this information down to 10 m below the ground surface along selected transects. The vertical structure of the earthflow, down to the substratum, is defined precisely thanks to joint inversion of DC and TDEM vertical soundings along one profile: the flowing upper layer and the position of the substratum are clearly evidenced. Combining this geophysical datasets with geotechnical tests and drill holes, we provide an estimate of both the location and the volume of the potentially most dangerous areas of the earthflow.

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1. Introduction

Earthflows are rather widespread phenomena over the world (Keefer and Johnson, 1983; Flageollet, 1988; Dikau et al., 1996; Flageollet et al., 1999). They are regularly affecting and killing people, and damaging present inhabitations and structures, as well as archeological sites. As a consequence, numerous international programs are dedicated to their study like the SAMOA program of the European Community, the International Geological Correlation Program from UNESCO (“Landslide Hazard Assessment and Mitigation for Cultural Heritage Sites and Other Locations of High Societal Value”), and the program “Catastrophes Environnementales” in France.

The southern Alps are severely affected by earthflows, especially in the Callovo-Oxfordian black marls (termed “Terres-Noires” in French) of the Barcelonnette basin (Fig. 1a). In this region several active earthflows affect parts of the torrential basins. These active complex landslides

occur on strongly gullied slopes. They usually associate landslides upstream with earthflows downstream (Flageollet et al., 2000; Malet et al., 2004; Remaître et al., 2005). Super Sauze is an important earthflow within this part of the French southern Alps (Fig. 1b).

The aim of this contribution is twofold. We first want to draw a geohazard map of the Super Sauze earthflow. In addition, we want to demonstrate how geophysical (minimally invasive) data can help to determine the 3D internal structure of such an earthflow.

2. Prior knowledge regarding the Super Sauze earthflow

2.1. Morphology

The Super Sauze earthflow occurred in a gullied torrential basin. Its present topography appears as roughly parallel crests and gullies, with a specific morphology of blocks and packs of marls that broke away from the main scarp (located at an altitude of 2105 m) through plane ruptures. The accumulation of these materials produces progressively a heterogeneous flow in the lower part of the structure. The toe of the moving mass is presently at an altitude of 1740 m. The flow has progressed over a distance of 800 m since it started.

The local substratum is made up of black marls. It is a compact formation with a black shale facies that can be seen at the main scarp,

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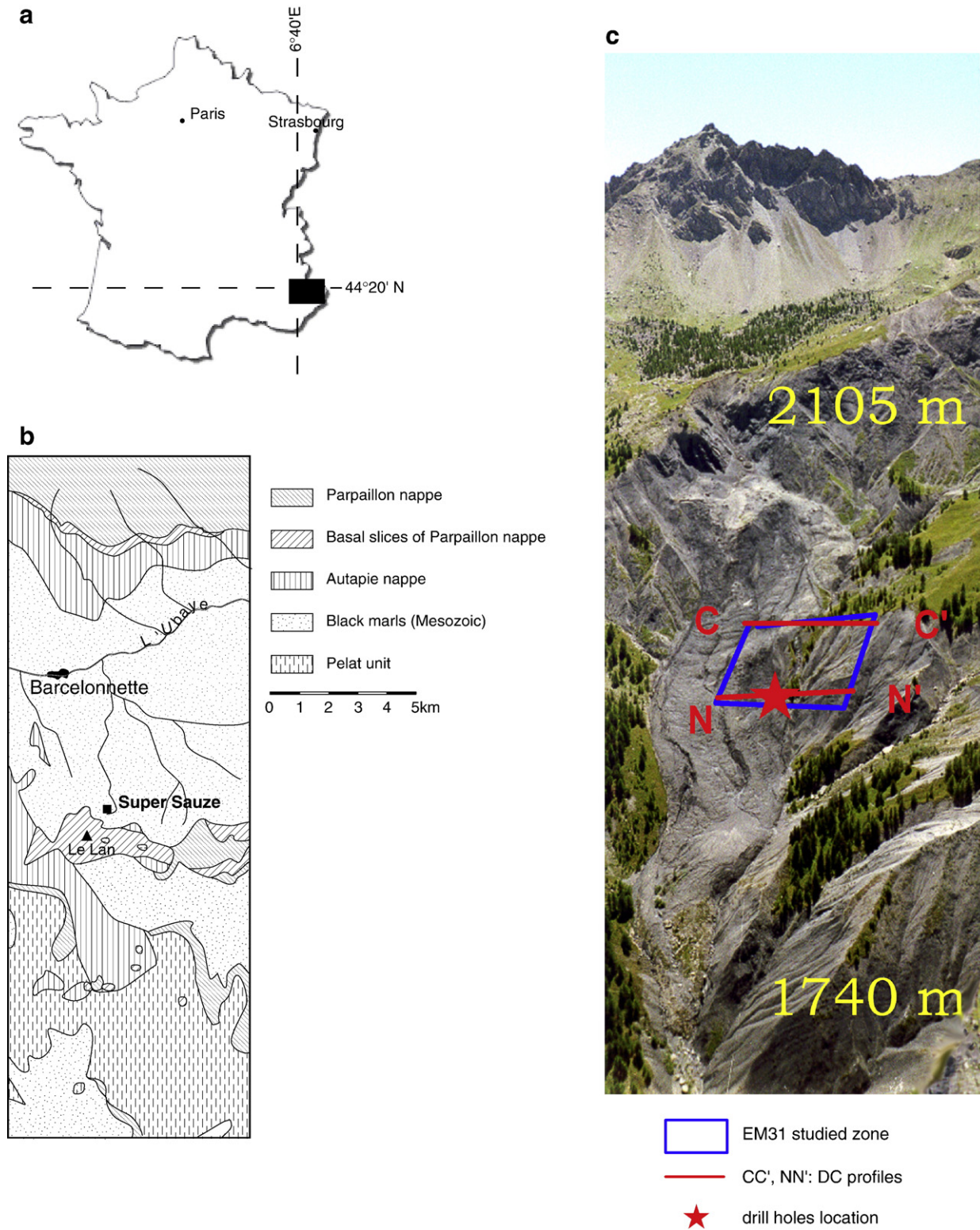


Fig. 1. a) A Super Sauze landslide (French Alps, France) aerial photography with location. b) Geological map related to Super Sauze landslide.

at the flanks of the lateral gullies and it is outcropping at three places within the accumulation zone (Flageollet et al., 1996). The debris-flow is characterised upstream by dislocated and fractured blocks of black marls which vary in size from a few cubic meters to several tens of cubic meters. Down slope, these ridged blocks turn into a rough surface of crumbling blocks and then into weathered rounds and smooth fragments. Downstream, the uneven surface of the earthflow is made up of a moraine calcite pebbles floating into an heterogeneous

fairly fine marl and clays matrix with weathered stones and flakes of various sizes (Flageollet et al., 2000). In the wettest zones of the earthflow, the material becomes a rather liquid mud.

Surface drainage of the meteoric water operates via small gullies and rills, in addition to three major gullies. The main axial gully has intra-flowing with intermittent run-off. Two lateral gullies have perennial run-off. One of them is incised into the in situ marls while the second one is flowing within the debris-flow (Figs. 1a and 2).

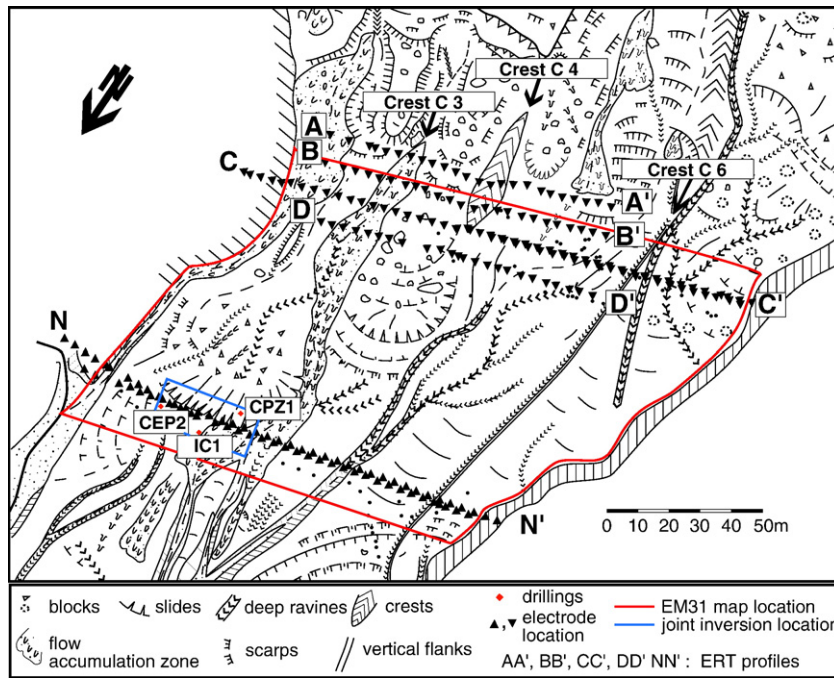


Fig. 2. Gemorphological map superimposed with geophysical investigation features – location map: EM 31 – ERT profiles – TDEM soundings – drill holes.

2.2. Direct investigations

Numerous direct investigations were carried out before and during the geophysical surveys. They include both drill holes (indicating the vertical succession of the main horizons, down to the substratum) and over 100 penetrometer and pressiometer geotechnical tests. These tests enable to divide the flow vertically into two main units based upon geotechnical criteria. (Flageollet et al., 2000).

From this data set, we can observe a near surface unit, 5 to 9 m thick, characterised by rather low mechanical resistance and pressiometric moduli (<10 to 15 MPa), as well as by surface velocities greater than 5 m/year. This layer is the most active layer of the earth flow. It is made up of wet and viscous mud. Tension cracks are also observed and it is clear that they influence the water recharge of the aquifer. Groundwater level fluctuation ranges from 0.5 to 1.5 m below the ground surface.

A deeper unit, 5 to 10 m thick, can be also drawn from these data. Its maximum thickness occurs in the central part of the earthflow. The distinction between these two layers is based upon inclinometric measurements and results of the pressiometric tests (modulus >15 MPa). We infer that this deeper unit is stiff, highly compact, dry and either a stable “dead body” or moving material with a very low velocity.

2.3. Previous geophysical results

Caris and Van Asch (1991) were the first to perform electrical, electromagnetic, and seismic measurements plus hydraulic conductivity measurements. The obtained results, while very interesting, were not accurate enough for to assess a map of the geohazards associated with the Super Sauze earthflow. Schmutz et al. (2000) performed the joint inversion of TDEM and DC soundings at five locations. They observed thin conductive layers separating the upper active formation from the more passive lower one and finally from the more resistive black marl substratum. In addition, the thickness and the resistivity of the upper active formation was observed to vary laterally along the traverse in agreement with the conductivity map, i.e. the central part of the body is the most resistive one (in the range 40 to 50 Ω m) whereas the eastern edge is the most conductive one (in the range from 19 to 23 Ω m). This

observation can be tied to the clay and water contents of the formations and will have consequences on the potential motion velocity of the earthflow as discussed below. Schmutz et al. (2000) observed also that the lower more passive formation is approximately four times more resistive than the upper active one. Its lateral variations are reasonably similar to the ones above. Finally, they observed that the black marl substratum is the most resistive structure of all formations with values of the order of, or higher than, 400 Ω m.

A new joint inversion of this data set was performed using Semdi software (HGG Ltd.). Three important points may be emphasized: (i) the important uncertainty in the resistivity distribution of the thin shallow layers (this means that only the total resistance of these layers as a whole can be resolved), (ii) the necessity of a model of at least 4 layers in total to fit the DC and TDEM data. This leads to the results reported in Table 1. (iii) The need to combine DC and TDEM to ensure good sensitivity up to an average depth in the range 15 to 20 m.

Grandjean et al. (2007) and Meric et al. (2007) performed additional works related to the same earthflow by combining electrical resistivity and seismic tomographies to define altered zones from the substratum. Even if the approach is different from the methods outlined above, the results are complementary with the other works discussed above. Because of these various works, the earthflow of SuperSauze can be considered as a test area for geophysical investigations.

3. Methodology

3.1. Geophysical approach

The location of the corresponding geophysical profiles is shown on Figs. 1c and 2. The main relevant geophysical parameters are: (i) the

Table 1
New joint model fitting to DC and TDEM data.

Layer	Resistivity	Thickness
1	40–50	5–7
2	5–6	2–3
3	30–40	5–7
4	180	

mechanical resistance variation between the moving unit, the “dead body” unit, and the substratum (as observed by seismic data), (ii) and the variation in the water content between the same layers (measured by the EM and electrical methods). The principal interest of seismic data is that their high comparability with the available geotechnical tests. In addition, electromagnetic (EM) and electrical methods are appropriate techniques to determine the spatial variations in the water content.

The strategy we followed is now outlined. We performed a detailed EM31 map to obtain resistivity information down to a depth of 4–5 m below the ground surface. This method is easy to implement in the field but it can be only used to investigate the shallow subsurface. In addition

to this map, we performed few DC and TDEM soundings at the same locations to obtain a better vertical distribution of the resistivity through joint inversion of these data (DC or TDEM data proceeded separately may not be precise enough). Some drillings are also necessary to validate the geophysical interpretation. ERT profiles are used here as a support, to validate the vertical resistivity interpretation.

When all these data from various tools seem compatible, we can extrapolate the interpretation into potentially moving or, at the opposite, stable surface, that is in a map of the geohazard risk. We therefore propose a risk assessment consisting in the localization of the potentially rapidly moving masses and the estimation of their minimal volume.

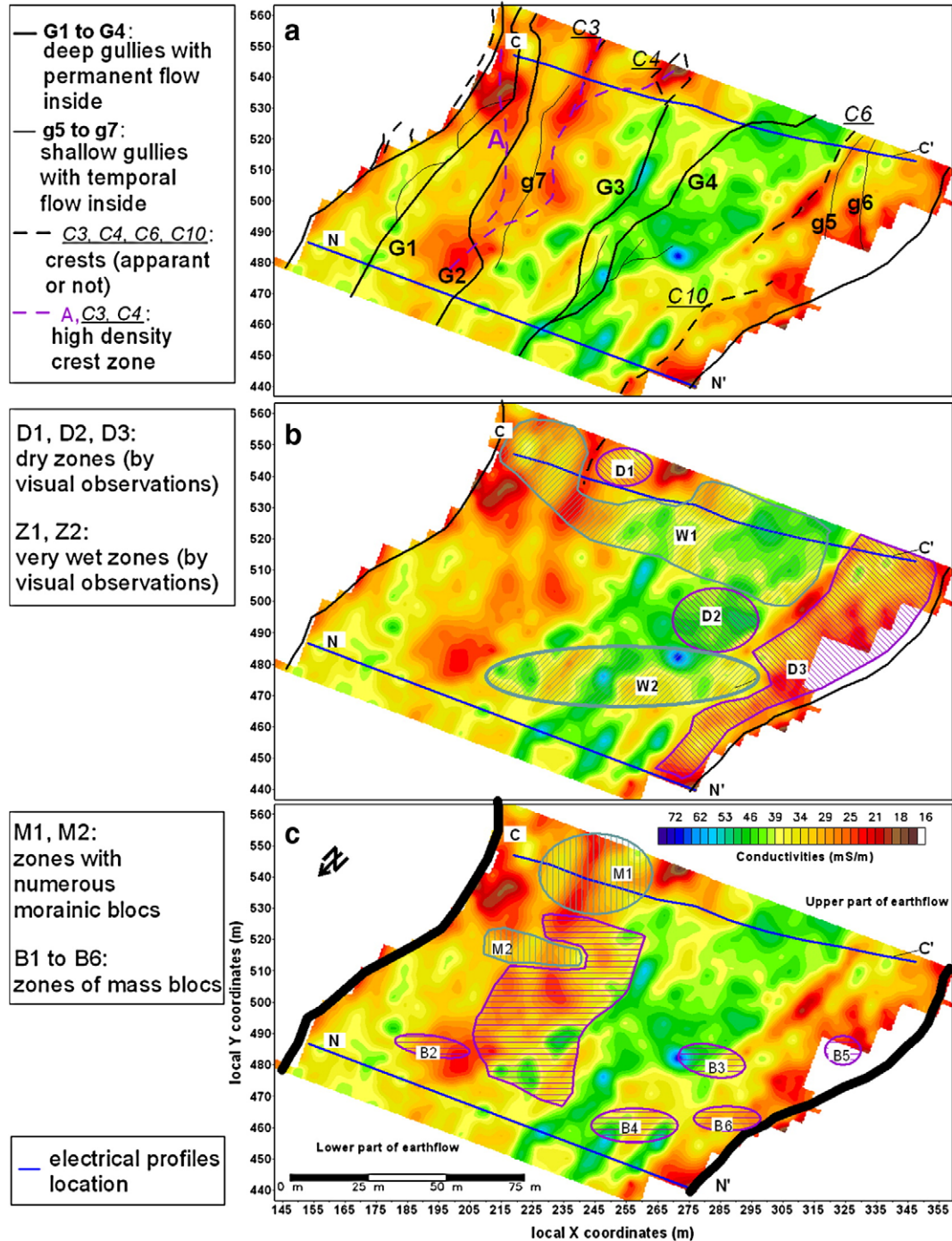


Fig. 3. Conductivity map superimposed with surface evidences and geomorphological features. a) gullies and crests, b) dry and wet zones, and c) morainic and mass blocs.

3.2. Geophysical methods lay out

3.2.1. Low Induction Number Frequency Domain Electromagnetism – EM31

The EM-31, implemented with a Geonics EM 31 Instrument (McNeill, 1980), is widely used for environmental surveys. Measurements have been acquired in October 1998. However, it has been scarcely applied to earthflow studies. The dimensions of the investigated area are approximately 100×150 m. It is limited upstream, in the south, by profile CC' and downstream, to the north, by profile NN' (see Fig. 2). Measurements were carried out along lines that are normal to the direction of the earthflow, 10 m apart of each other. Along each line, the stations were approximately separated by 5 m. The classical Horizontal Coil Configuration (HCP) with the measuring device located approximately 1 m above the ground was used. In spite of the rough topography mentioned above, measurements are repetitive and of high quality. The final output is an “apparent conductivity” map discussed below (see Fig. 3).

3.2.2. DC-resistivity measurements

The DC-resistivity measurements have a relatively long history concerning the application of this method to landslides (see Bogoslovsky and Ogilvy, 1977; Cassinis et al., 1982; Cummings and Clark, 1988; Palmer and Weisgarber, 1988). During the last decade, Electric Resistivity Tomography (ERT) has been widely used for high resolution applications. For instance Batayneh and Al-Diabat (2002) used this method to evaluate the potentially unstable volume of a landslide while Fikos et al. (2002) used it to map seasonal changes of the water-table. Hauck and Vonder Mühl (2003) used DC-resistivity to detect near surface ground ice occurrences and Lapenna et al. (2003; 2005) to understand the influence of water content on three different landslides.

Because ERT turns out to be a non-stand alone method to image precisely and unequivocally the ground subsurface, it has often been combined with other geophysical techniques: Jongmans et al. (2000) combined it with seismic tomography; Bichler et al. (2004) added GPR to achieve a 3D mapping of a landslide; Perrone et al. (2004) included self potential to identify sliding surfaces; Godio et al. (2006) combined ERT, seismic refraction tomography and spectral analysis of surface waves, and finally, Grandjean et al. (2006) associated ERT with seismic tomography to characterise the mechanical properties of earthflow. For a more thorough review on geophysical methods employed to investigate landslides, refer to Jongmans and Garambois (2007).

In our studied area (Fig. 2), two profiles were first covered (CC' and NN'). The pole–pole array was selected with a specific logarithmic progression for the TX–RX distances: the minimum distance was equal to 0.6 m, whereas the maximum was either 43 or 68 m, depending on both the available space and the topography. The electrodes at infinity were approximately 300 m away from the profile, upstream (B) and downstream (N) along the flow axis. Three additional profiles (AA', BB' and DD') were then considered, close to the initial one (CC'), in order to study the variations, downstream. Measurements have been carried out in October 1997.

3.2.3. TDEM

The TDEM or Transient ElectroMagnetism method (TEM) is a controlled source electromagnetic method (Nabighian and Macnae, 2005). This technique is widely used for saline intrusion and mineral prospecting, but it has been scarcely applied to earthflows. We used the PROTEM 47 (Geonics Ltd.) with an offset configuration. The following parameters were used to detect the substratum (located at a depth comprised between 20 to 30 m below the ground surface) and to ensure a good lateral resolution: a 5 m×5 m square coil, a 12.5 m offset between the transmitter and the center of the receiver coil, a turn of time of 0.5 µs, and a repetition rate of 237.5 Hz. This lay out allows easy use and optimal signal/noise ratio, while avoiding saturation. The appropriate spacing between the measurement points to investigate

the lateral heterogeneity is 5 m. Measurements were performed in October 1997.

4. Results

4.1. Shallow conductivity map (EM31) superimposed to morphological features

The conductivity map (Fig. 3a, b, and c) shows well-organised features, which roughly run parallel to the earthflow between 1 and 5 m depth. Three main zones are clearly identified. They correspond to (i) a narrow resistive region (conductivities smaller than 40 mS/m), approximately 25 to 30 m wide. This region bounds the earthflow to the West. (ii) A wider resistive zone, up to 75 m wide, that bounds the earthflow to the South as well as to the East. Note that a narrow and short conductive zone also appears in the extreme North-East of this region. (iii) A major conductive axis runs close to the center of the earthflow, slightly shifted to the West, and exhibiting conductivities over 40 mS/m.

We investigate now the correlation between the geophysical data and the crests and the gullies (see Fig. 3a). The concordance between the main visible crests (C10, C6, C4, and C3) and the resistive axes is fairly reasonable. The conductivity map shows that C4 and C3 are to be extended downstream, which is confirmed by the geotechnical data. Two deep gullies (G4 and G3) are located within the main conductive anomaly. A similar correlation is observed for G1 in the North. G2, on the other hand, has almost no signature on the conductivity map. Small temporary gullies (g5 to g7) have also no signature in the conductivity map. In summary, the conductivity map generally confirms the deep morphological features. It maps additional hidden features of similar nature and enhances the differences between shallow features and deeper ones.

We discuss now the correlation of the conductivity map with the observed surface conditions (see Fig. 3b and c). Most of the so-called “dry zones” (D1 to D3) are located within the resistive areas with the notable exception of D2, which is in the middle of the conductive region. The wet zone W2 is located within the conductive anomaly, whereas W1 crosses the whole flow, from East to West. In other words, it goes through the conductive as well as the resistive anomalies.

The two spots showing numerous moraine blocks (M1 and M2), which should correspond to stabilized zones, are located in the Eastern resistive zone. The six zones which show massive blocks (B1 to B6) are rather randomly distributed within the resistive and the conductive zones.

It can thus be concluded that from surface conditions alone, as observed from direct inspection, erroneous conclusions could easily be drawn, when it comes to characterise the most active part of the earthflow, i.e. the approximately 5 m-thick upper layer. The electromagnetic conductivity map appears therefore an important tool to reach proper conclusions concerning the potential danger of the sliding masses.

4.2. Electrical Resistivity Tomography – lines AA' to DD' (Fig. 4)

The difference between the two southern profiles (AA' and BB') located upstream, just outside the area studied with the EM31, and the two northern ones (CC' and DD') belonging to the study area is striking. Indeed, a slightly resistive (80 to 130 Ω m) and broad body clearly outcrops in the central part of lines AA' and BB'. This is in agreement with the visible crests of black marls. On each side and especially to the West, it is covered by a thin layer of potentially moving clays and marls (Fig. 4).

Lines CC' and DD': the resistive body has moved to the East and it deepens, downstream. The two crests C3 and C4 (shown on the previous conductivity map) can be mapped on this section as well. The layering is rather smooth to the West, which means that no crest is visible. The

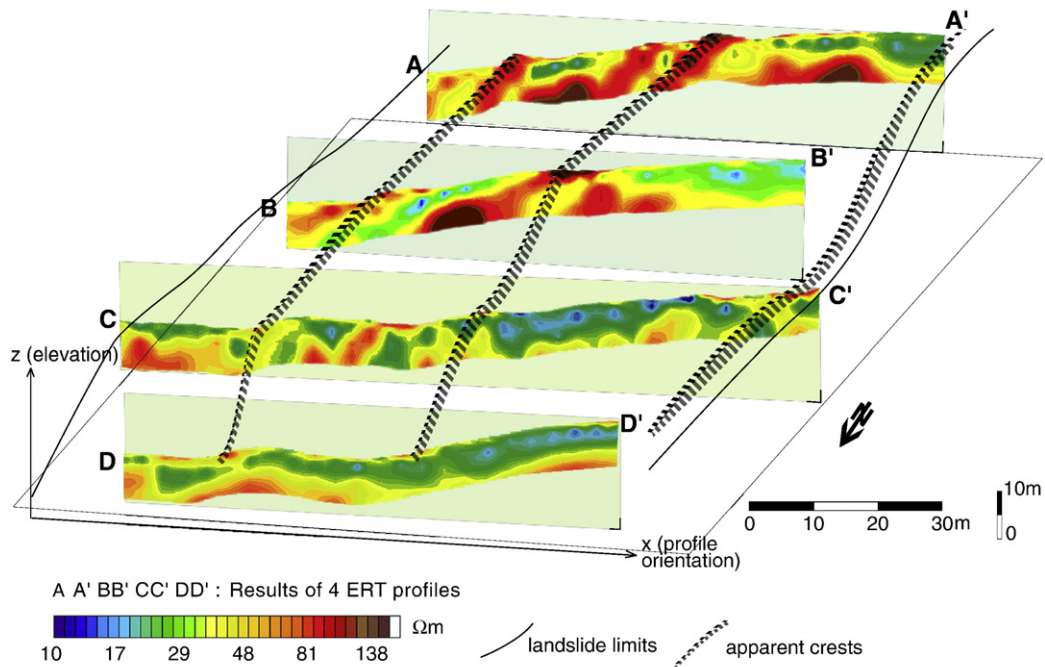


Fig. 4. ERT profiles. Evolution of resistivity through 4 profiles with apparent crests superimposed.

resistivity values increase regularly with depth, but they barely reach 80 Ω m, which means that the substratum is scarcely reached.

5. Discussion and risk assessment

The information obtained from geophysics is synthesised in two block-diagrams (Figs. 5 and 6). Fig. 5 concerns near-surface data. The aerial photographs show distinctly the gullies (thin black lines) and the mass rolls (essentially the white surfaces). These features seem poorly connected to the internal structure of the active sliding body

and more to the dynamic of the earthflow. The conductivity map concerns the first 5 m. It provides new and relevant information as mentioned above: hidden crests on one hand, and spatial distribution of specific clay and/or water contents of the potentially moving mass on the other hand. The ERT data to the south of the studied area confirms these results. The two northern profiles (CC' and DD') clearly belong to the area where the upper layer is beginning to thicken.

The second block diagram (Fig. 6) shows the conductivity map transformed into a map attempting to predict the potential motion of the moving mass. This is a crucial information to use for risk assessment.

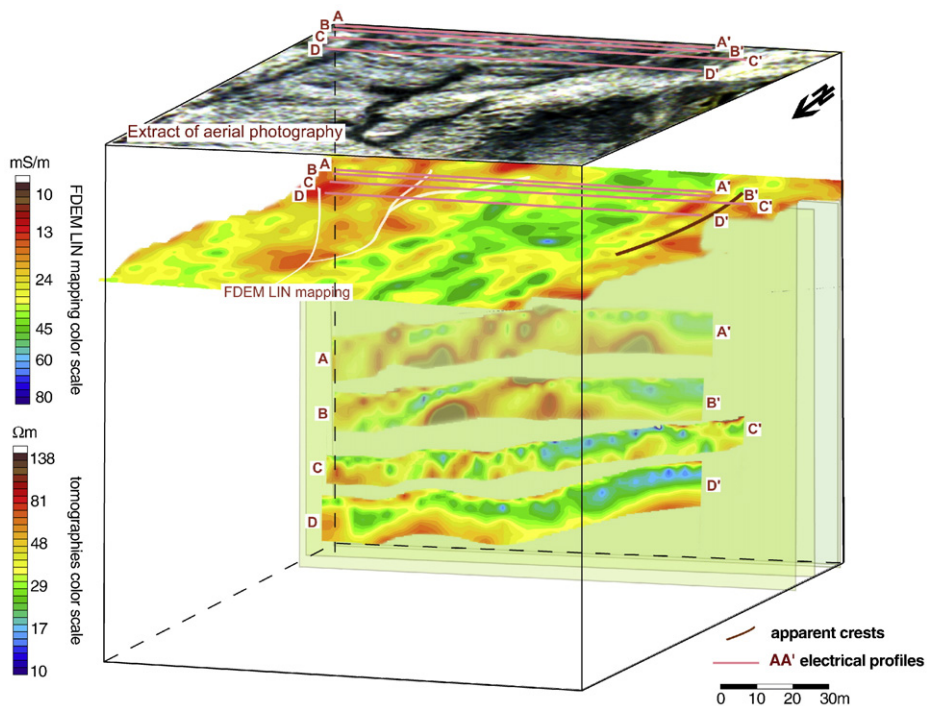


Fig. 5. Near surface information – synthetic bloc diagram. Extraction of moving mass (green), from non-moving mass (red) and transition zone (yellow) from EM31 map combined with joint inversion results.

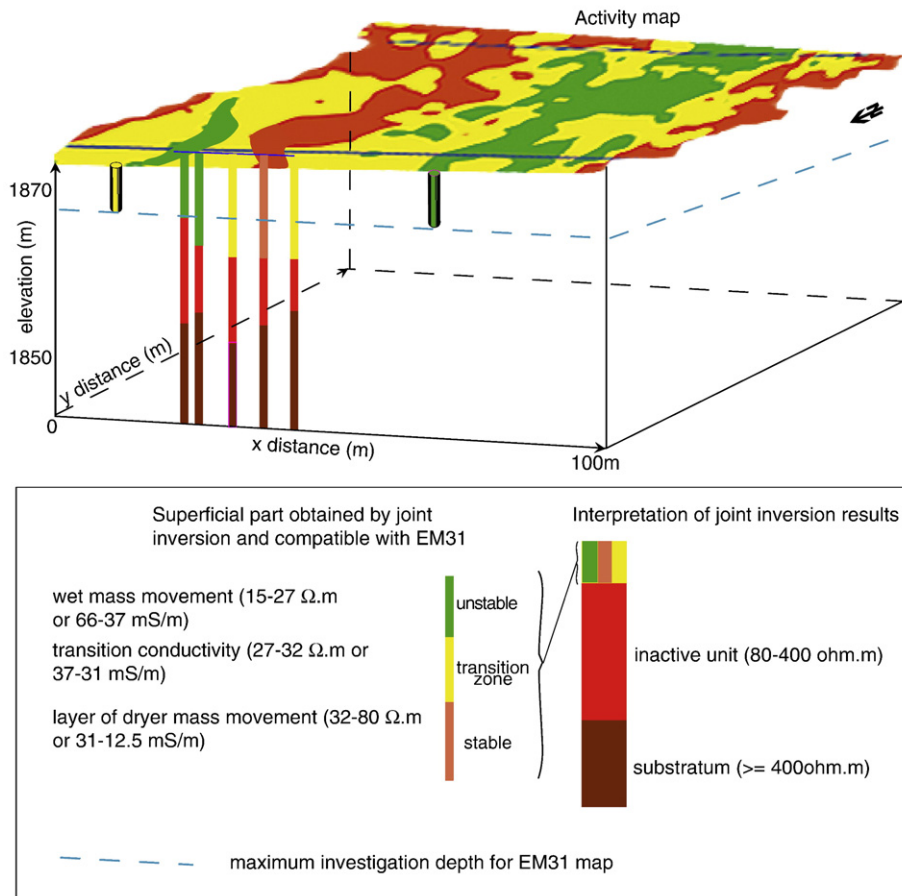


Fig. 6. Electrical and electromagnetic information – synthetic bloc diagram. Contribution of fast EM31 map to lithological setting with the help of ERT profiles, to the opposite of aerial photography.

Even if the measurements were not made at the same time, they look comparable. This might be explained by the fact that the topography surface is evolving quickly. However, the modification of the subsurface occurs on a larger time scale.

The conductivity values, measured by the EM 31 tool, can be considered as representative of the upper layer down to its maximum depth of investigation, i.e. down to 5 to 6 m, along profile NN'. This is demonstrated by the agreement between the relative lateral variations, from East to West, of the resistivity on one hand and the conductivity on the other hand (see the joint inversion of the soundings and by EM 31, Fig. 5). Assuming that this statement can be generalised to the whole studied area, there is a direct link between the clay and the water content of the upper layer and its potential motion. Therefore the conductivity map can be transformed into a map describing approximately the ability of the sliding body to move. Three classes are proposed. The first one corresponds to rather stable units (conductivity smaller than a threshold value of 31 mS/m). They represent approximately 23% of the total area. The second class corresponds to the most active units (conductivity higher than 38 mS/m). This second class concerns about one third of the total area. Finally, a third class corresponds to intermediate units, which represent around 44% of the whole area. From these ratios, it could be inferred that a maximum of 33% of the studied area (units 2 only) could potentially lead to torrential flow, while an additional 44% (units 3) could ultimately join the flow at lower speeds; the last 23% (units 1) corresponding to the most stable part of the layer. Within the studied area, the major place from which the flow might originate is located slightly in the west of the axis of the valley. A second minor source might be located to the north-east of the area.

The vertical structure of the moving mass is precisely determined along Line NN' thanks to additional data corresponding to three boreholes and five geophysical soundings. The existence of the thin intermediate layers that separate the main units is of importance to understand the dynamic of the earthflow. The thickness of the upper layer varies from 4 to 10 m. With the information obtained with the penetrometer, it is assumed, for a first rough risk evaluation, that these approach can be generalised to the whole studied area. Assuming therefore an average thickness of 5 m for the upper layer over the whole studied area, approximate values of the volume of the potentially moving masses can be estimated from its size (150 m × 150 m) and the surface ratios mentioned above. The volumes would then be equal to 140 000 m³ for units 2 alone and to 350 000 m³ for units 2 and 3 together. Considering that the area of interest represents approximately 30% of the whole Super-Sauze earthflow, the total volumes of the corresponding fast moving masses would be of the order of 470 000 m³ (units 2) and 1 200 000 m³ (units 2 + 3). These extremely rough preliminary maps are definitely open for discussion and for additional controls in the field, before introducing them into any risk assessment project.

6. Conclusions

A geophysical survey based on a combination of electromagnetic and electric techniques leads to two types of conclusions. The first one concerns the Super Sauze earthflow itself, while the second one relates to the methodological application of geophysics to the study of similar landslides.

Concerning the Super Sauze earthflow, three types of information have been obtained thanks to geophysics, they are of high importance

to both understand the dynamics of the flow and to assess the underlying risk:

- (1) A detailed structural map of the active upper layer has been achieved using a dense shallow electromagnetism survey. This map enlightens a number of structural features that could not be inferred from remote sensing and direct visual interpretation alone.
- (2) A detailed knowledge of the vertical structure of the earthflow at specific locations leads to a model with 6 layers, including 2 thin interfaces between the main units. This valuable information also quantifies thicknesses in good concordance with nearby wells (Schmutz et al., 2000).
- (3) From the various sources of information, we have determined preliminary and rough estimations of the volumes of the potentially fast moving masses, and we have localized the most likely areas from which the flow might originate.

Two major conclusions are drawn regarding the geophysical methodology to be applied to study similar earthflows. First, a high density of shallow electromagnetic data (EM 31) is recommended to be carried out just after remote sensing techniques and visual field observations have been applied and before any drilling is undertaken. From these three preliminary investigations, a first model can be built and control drill holes are then proposed and executed. One might wish to use also a deeper high density electromagnetic mapping tool (EM 34), in addition to the shallow one, to better evaluate the depth extension of the features which have been mapped by the first survey. The next stage consists then in detailed geophysical investigations at selected spots decided upon discussions between all partners (geographers, risk experts, geologists, geotechnical experts, hydrogeologists and geophysicists). The resistivity tomographies, if well integrated into the results of joint inversion and boreholes data, can contribute to produce a 3D image of the subsurface lithological settings. The lateral resolution of these tomographies is well adapted to reach this goal while its vertical resolution and depth of investigation are however limited. High resolution seismic surface tomography might be a good alternative.

When a detailed knowledge of the vertical structure is sought for at selected spots, it has been proven that a single DC or TDEM sounding cannot solve the problem and the joint inversion of both soundings remains the most efficient approach to define the vertical structure of the body. Seismic refraction alone would probably not permit to distinguish among the thin interface layers which have been mapped by combination of electrical and electromagnetic soundings.

References

- Batayneh, A.T., Al Diabat, A.A., 2002. Application of a two-dimensional electrical tomography technique for investigation landslides along the Amman-Dead Sea highway, Jordan. *Environmental Geology* 42 (4), 399–403.
- Bichler, A., Bobrovsky, P., Best, M., Douma, M., Hunter, J., Calvert, T., Burns, R., 2004. Three-dimensional mapping of a landslide using a multi-geophysical approach: the Quesnel Forks landslide. *Landslides* 1, 29–40.
- Bogoslovsky, V., Ogilvy, A., 1977. Geophysical methods for the investigation of landslides. *Geophysics* 42, 562–571.
- Caris, J.P.T., van Asch, T.W.J., 1991. Geophysical, geotechnical and hydrological investigations of a small landslide in the French Alps. *Engineering Geology* 31 (3–4), 249–276.
- Cassinis, G., Dal Piaz, G.V., Semenza, E., Vai, G.B., Spalletta, C., 1982. Geological and geophysical model of northeastern Italy and its relationship to the Apennine. 71st Congress of the Geologic Society of Italy, pp. 79–87.
- Cummings, D., Clark, B.R., 1988. Use of seismic refraction and electrical resistivity surveys in landslide investigation. *Bulletin of Association Ang. Geology* 25 (4), 459–464.

- Dikau, R., Brunsden, D., Schrott, L., Ibsen, M.L., 1996. *Landslide Recognition/Identification, Movement and Causes*. Wiley, 251 pp.
- Fikos, I., Vargemezis, G., Tsokas, G.N., Hatzidimitriou, P., Dimopoulos, G., 2002. Diachronic study of free aquifers using the method of electric tomography: a case study in northern Greece. *European Journal of Environmental and Engineering Geophysics* 7, 185–193.
- Flageollet, J.C., 1988. *Les mouvements de terrain et leur prévention*. Masson Ed. 224 p.
- Flageollet, J.C., Malet, J.P., Maquaire, O., 2000. The 3D structure of the Super Sauze flowslide: a first stage towards its behaviour modeling. *Phys. and Chem. of the Earth; EGS Journal. Monitoring, Modelling and Mapping of Mass Movements. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, vol. 25(9), pp. 785–791.
- Flageollet, J.C., Maquaire, O., Martin, B., Weber, D., 1999. Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern Alps, France). *Geomorphology* 30 (1–2), 65–78.
- Flageollet, J.C., Maquaire, O., Weber, D., 1996. Geotechnical investigations into the Super Sauze landslide. *Geomorphological and hydrogeological results*. Workshop “Landslides and Flash flood”, CERG, Barcelonnette – Vaison la Romaine du 30-9 au 3-10, pp. 30–38.
- Godio, A., Strobbia, C., De Bacco, G., 2006. Geophysical characterisation of a rockslide in an alpine region. *Engineering geology* 83, 273–286.
- Grandjean, G., Malet, J.P., Bitri, A., Meric, O., 2007. Geophysical data fusion by fuzzy logic for imaging the mechanical behaviour of mudslides. *Bulletin de la Societe Geologique de France* 178 (2), 127–136.
- Grandjean, G., Pennetier, C., Bitri, A., Meric, O., Malet, J.P., 2006. Caractérisation de la structure interne et de l'état hydrique de glissements argilo-marneux par tomographie géophysique: l'exemple du glissement-coulée de Super Sauze (Alpes du Sud, France). *Comptes Rendus des Geosciences* 338, 587–595.
- Hauk, C., Vonder Mühl, D., 2003. Inversion and interpretation of two-dimensional geoelectrical measurements for detecting permafrost in mountainous regions. *Permafrost and periglacial processes* 14, 305–318.
- Jongmans, D., Garambois, S., 2007. Geophysical investigation of landslide: a review. *Bulletin of the French Geological Society* 178 (2), 101–112.
- Jongmans, D., Hembrouille, P., Demanet, D., Renardy, F., Vanbrabant, Y., 2000. Application of 2D electrical and seismic tomography techniques for investigating landslides. *European Journal of Environmental and Engineering Geophysics* 5, 75–89.
- Keefer, D.K., Johnson, A.M., 1983. *Earth flows: morphology mobilization and movement*. Geological Survey Prof. Paper 1264. US Govern. Print. Off., Washington, 56 pp.
- Lapenna, V., Lorenzo, P., Perrone, A., Piscitelli, S., Rizzo, E., Sdao, F., 2005. 2D electrical resistivity imaging of some complex landslides in the Lucanian Apennine chain, southern Italy. *Geophysics* 70 (3), B11–B18.
- Lapenna, V., Lorenzo, P., Perrone, A., Piscitelli, S., Sdao, F., Rizzo, E., 2003. High-resolution geoelectrical tomographies in the study of the Giarossa landslide (southern Italy). *Bulletin of Engineering Geology Environmental* 62, 259–268.
- Malet, J.M., Maquaire, O., Locat, J., Remaître, A., 2004. Assessing debris flow hazards associated with slow moving landslides: methodology and numerical analyses. *Landslides* 1, 83–90.
- McNeill, J.D., 1980. *Electromagnetic terrain conductivity measurement at low induction numbers*, Technical Note TN-6, Geonics, 15 pp.
- Meric, O., Garambois, S., Malet, J.P., Cadet, H., Gueguen, P.H., Jongmans, D., 2007. Seismic noise-based methods for soft-rock landslide characterization. *Bulletin de la Societe Geologique de France* 178 (2), 137–148.
- Nabighian, M.N., Macnae, J.C., 2005. Electrical and EM methods, In: SEG; 75; *Imaging the Past, Present, and Future*; Society of Exploration Geophysicists, The Leading Edge, 24, Suppl., S42–S45.
- Palmer, D.F., Weisgarber, S.L., 1988. Geophysical survey of the Stumpy Basin Landslide, Ohio. *Bulletin of the Association of Engineering Geologists* 25 (3), 363–370.
- Perrone, A., Iannuzzi, A., Lapenna, V., Lorenzo, P., Piscitelli, S., Rizzo, E., Sdao, F., 2004. High-resolution electrical imaging of the Varco d'Izzo earthflow (southern Italy). *Journal of Applied Geophysics* 56, 17–29.
- Remaître, A., Malet, J.P., Ancey, C., Locat, J., Maquaire, O., 2005. Flow behavior and runoff modelling in a complex debris flow in clay-shales basin. *Earth Surface Processes and Landforms* 30, 479–488.
- Schmutz, M., Albouy, Y., Guérin, R., Maquaire, O., Vassal, J., Schott, J.J., Desclôitres, M., 2000. Joint electrical and time domain electromagnetism (TDEM) data inversion applied to the Super Sauze earthflow (France). *Surveys in Geophysics* 21 (4), 371–390.

Further Reading

- Godio, A., Bottino, G., 2001. Electrical and electromagnetic investigation for landslide characterization. *Physical Chemical Earth* 26, 705–710.
- Schmutz, M., Guérin, R., Maquaire, O., Desclôitres, M., Schott, J.J., Albouy, Y., 1999. Contribution of a combined TDEM and electrical survey to the investigation of the Super Sauze flowslide internal structure. *Comptes Rendus de l'Académie des Sciences. Paris, Ila* 328, 797–800.