

# JOINT ELECTRICAL AND TIME DOMAIN ELECTROMAGNETISM (TDEM) DATA INVERSION APPLIED TO THE SUPER SAUZE EARTHFLOW (FRANCE)

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(Received 11 October, 1999; Accepted 22 July, 2000)

**Abstract.** In order to evaluate the risk of an earthflow to evolve abruptly into torrential surge, knowledge of its internal structure is necessary. This study deals with the internal structure of the Super Sauze earthflow developed in black marls in the southern French Alps. Difficulties in this study area are a rough topography, surface heterogeneities and a large thickness variability of the earthflow mass. These conditions hamper the application of geotechnical methods as a preferred investigation mean. Moreover, they pose problems to geophysical investigations and their interpretation.

This paper shows the advantage offered by the joint inversion of Time Domain ElectroMagnetism data (TDEM) and data obtained from Direct Current soundings (DC). The results of the joint inversions are checked using geotechnical data. The internal structure of the earthflow interpreted on the basis of joint inversion data is comparable to that obtained from geotechnical results. Moreover, contrary to separate electrical and TDEM inversions, a satisfactory joint inversion model can be derived without supplying additional *a priori* information.

**Keywords:** electrical and TDEM prospecting, earthflow, joint inversion, Simultaneous Electromagnetic Layered Model Analysis (SELMA) software

## 1. Introduction

In the southern Alps mountains (Figure 1), and particularly in the Callovo-Oxfordian black marls of the Barcelonnette basin (Alpes-de-Haute-Provence, France), several earthflows are active and affect several torrential basins (Julian and Martin, 1982). These active complex landslides occur on strongly gullied slopes and associate a landslide at the top of the mass and a flow at its downstream.

Since 1970, the Super Sauze flow mass covers a torrential basin (Figure 2). In order to evaluate the risk of a catastrophic evolution of the earthflow, it is necessary to know its volume and internal structure. The moving mass differs from the substratum for its water content and for its compactness. These characteristics



influence physical parameters like resistivity and seismic wave velocity, that can be measured by means of geophysical surveys. This paper reports the results obtained from measurements of electrical resistivity. The results of seismic refraction surveying, carried out in the same zone, will be a subject of a forthcoming work (Schmutz, 2000).

The site is characterised by complex conditions:

1. There is an irregular topography, the earthflow mass is strongly heterogeneous (there are blocks ranging in size from a few to several cubic meters), and moreover, the flow covers a torrential basin. This means that the substratum is composed of a succession of parallel gullies and crests that are more or less buried. The thickness of the flow varies between 0 and about 20 m.
2. The parent material of both the substratum and the earthflow is black marl. This implies that the resistivity difference between the flow mass and the substratum might be small. Indeed, the marls nominal resistivity given by Reynolds (1997) is 30–70  $\Omega$  m. But this value can vary as a function of the rock alteration, the water content, metallic mineral etc. (Archie, 1942). The differences in these properties between the substratum and the weathered material in the earthflow are sufficiently large to distinguish these layers on the basis of resistivity measurements.

The application of electrical techniques to mass movement investigations is well established (Palmer and Weisgarber, 1988, etc.). However, the application of TDEM in earthflow studies is new (Schmutz et al., 1999).

The problem with electrical and TDEM investigations interpreted separately is that both have certain limitations: electrical methods alone do not well define the characteristics of conductive layers, while the TDEM technique is not suitable to define resistive layers. That is why, in order to improve the assessment of the internal structure and to avoid the disadvantages of both methods, we realised a joint inversion of the two data sets.

The joint inversion of geophysical data was first attempted by Vozoff and Jupp (1975), but with reference to direct current and magnetotelluric data sets. Later, Raiche et al. (1985), Eckard et al. (1994) and Bredewout et al. (1996) inverted data sets from DC in a Schlumberger array, and TDEM in a central or coincident array.

However, to our knowledge, inversion of DC data in a pole-pole array with TDEM data in an offset array has not yet been carried out. In this paper this joint inversion is realised using the SELMA (Simultaneous Electromagnetic Layered Model Analysis) software (Christensen and Auken, 1992), slightly modified by two of the authors of the present paper (Yves Albouy and Jacques Vassal).

The objective of this study was to apply the modified software for a joint inversion of 1D data describing a 3D site, and to check the results by comparing them with those obtained from a geotechnical survey which was especially adapted to this complex site with a difficult access.

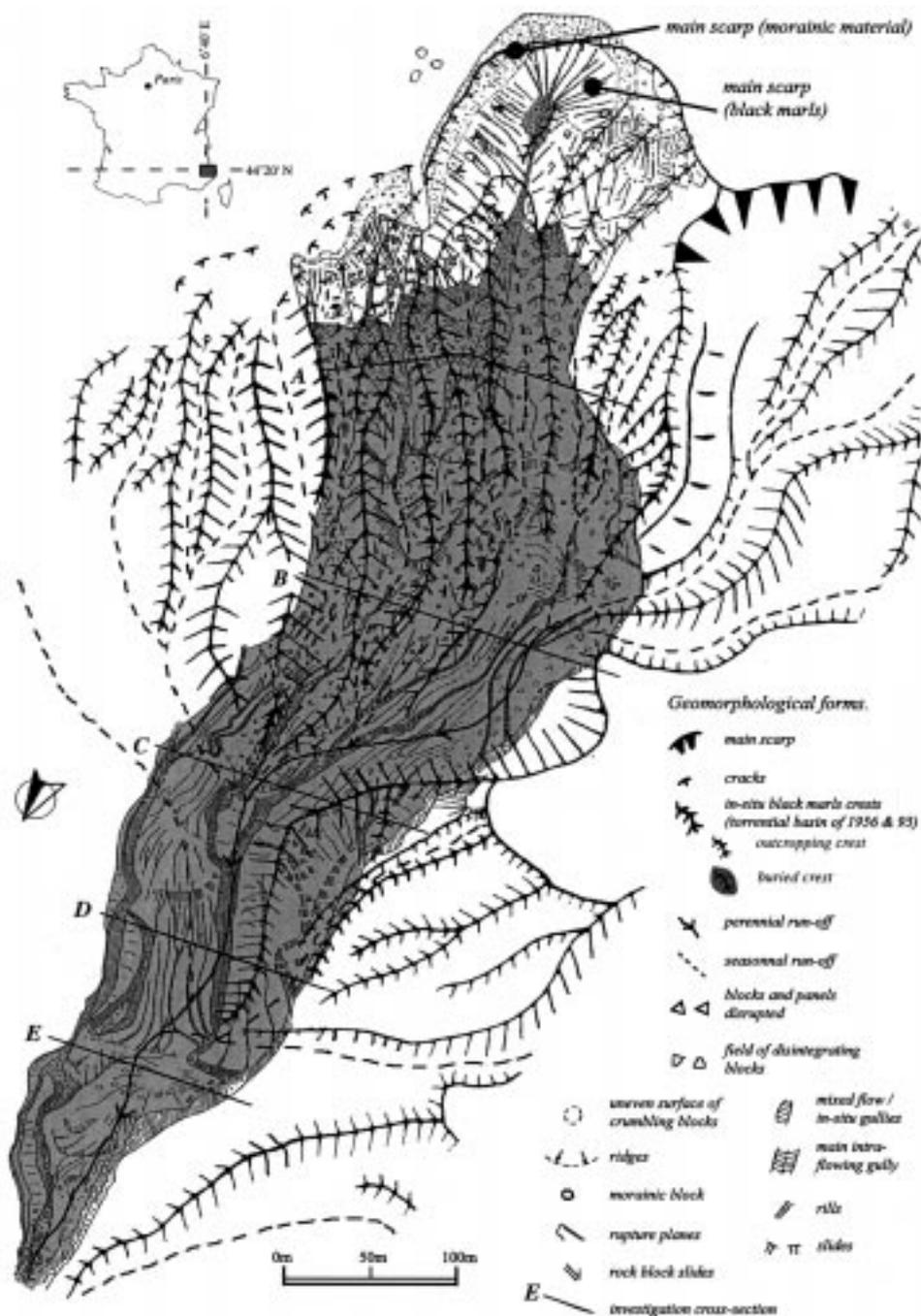


Figure 1. Location of Super Sauze earthflow, and Geomorphological map of Super Sauze earthflow with original crests (buried in the earthflow and visible in the torrential basin outside the earthflow).

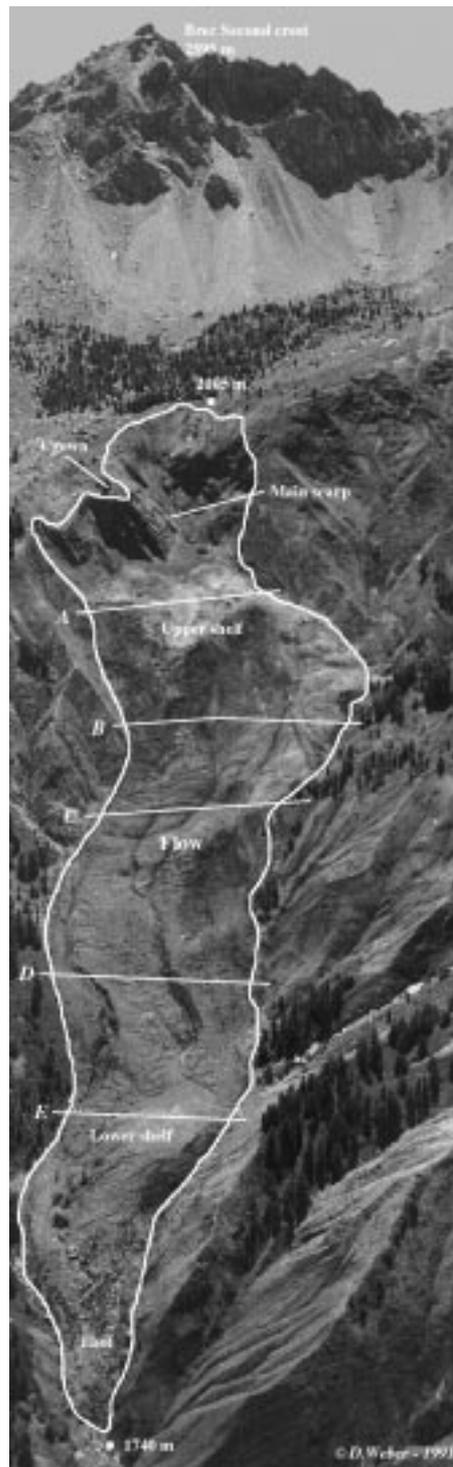


Figure 2. Aerial Super Saouze sight (1992) with permission of D. Weber.

## 2. General Framework

In a gullied torrential basin with a topography of roughly parallel crests and gullies (Figure 1), the Super-Sauze earthflow has a characteristic morphology of block marls that break away from the main scarp (2105 m) by plane ruptures, accumulate, progressively deform and result in a heterogeneous flow. 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 to move in the 1960's.

In the downstream direction the flow is characterised by a change of black marls structure. Further downstream, an area of dislocated and disintegrating blocks changes into an uneven, rough surface of crumbling blocks and finally into a slightly uneven surface scattered with calcite and moraine pebbles, weathered stones and flakes of various sizes. Surface drainage operates in small gullies, rills and in an axial main intra-flowing gully with intermittent run-off. Furthermore, there are two lateral gullies with perennial run-off (Figure 1), both incised into in-situ marls at one side and into the earthflow at the other side.

The in-situ marls reinforce the main scarp and the flanks of lateral gullies, and also crop out at three places in the accumulation zone (Flageollet et al., 1996). The marls are compact and comparable to black clay shale. In the overlying earthflow disintegrating slab stones and blocks of marls vary in size (from a few to several tens of cubic meters). With distance downslope these sharp blocks of marl turn into weathered, round and smooth fragments. These fragments fine downstream and are mixed in a heterogeneous marl-clay formation. This latter formation is composed of a matrix of fairly fine clay containing pebbles and crumbly flakes. In the wettest zone of the flow, this formation changes into a very liquid mud (Malet et al., in press).

The landslide morphology indicates that the moving mass covers a more or less intact paleotopography of roughly parallel crests and gullies. Depending on position and direction, this paleotopography has a significant effect on the thickness of the flow and on water pathways.

The phenomenon of earthflow is very widespread in the world (Keefer and Johnson, 1983; Flageollet, 1988; Zhang et al., 1991; Dikau et al., 1996; Flageollet et al., 1999). The Super Sauze earthflow has been the subject of several studies since the early 1990's: topographic monitoring since 1991 (Flageollet et al., 1996; Malet et al., 2000), multi-date photograph-interpretation (Weber and Herrmann, 2000), geotechnical investigation (Flageollet et al., 2000; Malet et al., 2000) and geophysical survey (Schmutz et al., 1999). The available expertise and background information about the study area is of great value for the present study.

For a geotechnical investigation, with the difficult accessibility (wet and muddy zones, large and deep gullies), 'light' investigation tools were chosen (dynamic penetrometer, percussion drilling) supplemented by 'heavier' tools (core sampling bore, destructive drilling). The general principle was to compare the results obtained by these various tools at several points, and then to extend the investigation

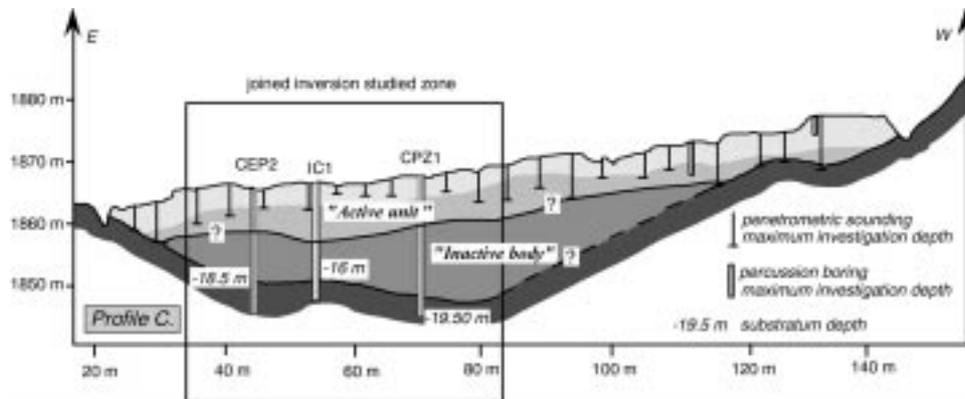


Figure 3. Geotechnical interpretation of the C transect from Genêt and Malet (1997); see Figure 1 for location.

to five cross-sections (A, B, C, D and E, in Figure 1) using the more handy tools such as the dynamic penetrometer (over hundred and fifty tests) and the percussion drilling (thirty borings). Geophysical surveys are situated near the geotechnical survey sections, but not exactly at the same place. That is why the geotechnical transect scale (Figure 3) is not the same as the geophysical one.

The reconstruction of the pre-event topography was based on both in situ investigation and photo-interpretation of 1956 and 1995 aerial ortho-rectified photographs. The pre-event relief can be relatively well-recognised on flanks of the flow, but is less obvious in the accumulation zone. The buried topography consists of a series of crests, almost intact in the accumulation zone. Three in-situ crests emerge more or less permanently from the flow near profile B. The flow is thickest in the axis of the buried main gully of the 1956 torrential basin (Figure 1).

Three 'geotechnical' layers can be identified in the flow based upon resistance criteria, contrasts in the nature of the soil and shearing of the inclinometric and piezometric tubes. The flow is composed of (Genet and Malet, 1997; Flageollet et al., 2000; Malet et al., 2000):

- a superficial unit 5 to 9 m thick (resistance of the rod ( $Qd$ ) < 10 MPa, pressiometric module ( $E_M$ ) < 15 MPa, surface velocity greater than 5 m/year). A potential internal slip surface has been identified at about 5 m depth on profile B and 8 to 9 m depth on profile C. According to the paleotopography and to the position of the groundwater table, this active unit can be subdivided in two sub-units (named respectively (1a) and (1b)).
- a deeper unit with a maximum thickness of 10 m on profile C and 5–6 m on profile B, with unknown internal characteristics. Based on the inclinometric measurements and the pressiometric trials ( $E_M > 15$  MPa, flow pressure ( $Pl$ ) > 4 MPa), we infer this is a highly compacted body, either stable or very slow by moving, as identified on the La Valette landslide (Colas and Locat, 1993).

Thus the accumulation zone is composed of two units, the upper unit is a very active and very wet viscous mud formation, whereas lower unit is a stiff compact rigid/plastic and stable formation (impervious material and dry conditions).

### 3. Geophysical Methods

The electrical resistivity is strongly dependent on parameters like granulometry and content of conductive materials (water, clay, metal minerals). Its measurement is thus a suitable tool for the study of earthflow structure. Surveys methods based on electrical and TDEM measurements allow to calculate the so called “apparent resistivity”. This parameter integrates the thickness and electrical resistivity of the layers constituting the soil. Then, the “real” resistivity is determined by solving the inverse problem, i.e., by proposing a model of the soil which would result in theoretical values as close as possible to those measured.

The first section describes the different field arrays employed to record the electrical and TDEM data. Subsequently, these data are analysed by separate inversions and then by using the joint inversion technique. The aim of this analysis is to show the advantage of this last process in the context of a complex 3D terrain situation.

#### 3.1. FIELD SET-UP

##### 3.1.1. *Electrical Survey*

The general principle of the survey by electrical sounding (ES), so called “direct current”, relies upon the injection of an electrical current between two electrodes, and measures a potential difference between two others (Kunetz, 1966). The objective of an electrical sounding is to measure resistivity variations with soil depth at one point. The set-up is carried out by increasing the measurement array. The measurements include more and more soil. Among the various geometrical configurations, the pole-pole array consists in using one electrode of injection and one of potential, whereas two others electrodes are known as ad infinitum, i.e., at a sufficiently large distance (ten to twenty times spacing between the two first and each other). This configuration has the advantage of employing a minimum of electrodes.

The equipment used in this study is the Syscal R1 (Iris Instruments) multi-electrodes with internal storage which contains so called “intelligent” electrodes. The latter are controlled by an electronic box containing a device which identifies the electrodes. The electrodes can have a potential or injection function, and can be made active or inactive.

The distance between two successive electrical soundings is four meters and the width of the transect is 144 m. We will present here the results of five representative soundings. The data were collected during two separate field experiments because of the restricted number of electrodes available (24):

- the first survey addresses the surface layers. The number of electrodes available makes it possible to carry out three soundings simultaneously. The electrode spacing follows a geometric progression, calculated to minimise the displacements of electrodes between two sequences of measurements: 0.6, 1, 1.6, 2.6, 4, 6.6 and 10.6 m.
- the second one is intended to increase the depth of investigation by programming spacings of: 10.6, 16.6, 26.8, 43 and 68 m.

Longer electrical arrays could not be set out because of lateral heterogeneities and rough topography (Figure 3). On the western boundary the torrent has created a 4 m deep and about 10 m wide incision. Moreover the opposite slope is very steep (50°), which poses obvious problems to carry out the measurements. To the east, steep slopes are encountered only 10 to 15 m beyond the earthflow limit and therefore the measurements could be slightly extended outside the earthflow.

Moreover, in spite of the reasonable maximum spacing (68 m), it is not sure if realistic substratum resistivities were obtained because of lateral variations problems that are increasing with the distance. Therefore, a complementary method was used to reach the substratum: the TDEM.

### 3.1.2. TDEM Survey

The TDEM (Time Domain ElectroMagnetism) or TEM (Transient ElectroMagnetism) is a controlled source electromagnetic method (Nabighian and MacNae, 1991; McNeill, 1994). An electromagnetic field, known as primary, is produced by a current in a transmitter coil. The abrupt turn off of this current generates a secondary electromagnetic field whose amplitude decays quickly. It is measured by a receiver coil in the absence of the primary field. The analysis of this decrease as a function of time makes it possible to quantify the distribution of the resistivities with depth. Measurements can be done *in situ* or from airborne survey. The configurations can follow central geometries (transmitter and receiver have the same centre), or with offset geometries (the receiver coil is placed outside the transmitter coil). The investigation depth depends on the characteristics of the transmission and of the subsurface. The main advantages of this method are the good ratio of the penetration depth over the space required by the layout, and a high sensitivity to the well-conducting soil layers. The main disadvantages are a rather poor resolution obtained for the resistive layers as well as a for the near surface layers.

The TDEM apparatus used for the survey is the PROTEM 47 (Geonics Ltd.).

This apparatus is recommended for the investigation of depths going from 2–3 to 150 m; the transmitting loops must be as close as possible to a square; the advised dimension of the transmitting loops for this apparatus varies in general from  $5 \times 5$  m for the smallest to 100 per 100 m for the biggest loop.

With respect to this transmitter loop variety, it is necessary to select the device best suited to the particular field specifications. The appropriate device should allow to reach the substratum (20–30 m of depth) and have a good lateral resolution.

After some trials, the following optimal configuration was selected: a  $5 \times 5$  m square coil, a 12.5 m offset between the transmitter coil centre and the receiver coil centre, a turn off time of  $0.5 \mu\text{s}$  and a frequency of 237.5 Hz. This layout allows us to reconcile easy use (more than 100 soundings were performed within in five days) with an optimal signal/noise ratio, while avoiding saturation. The spacing between the measurement points in the transect to investigate the lateral heterogeneity is 5 m.

Taking into account the heterogeneity of the site and set out type (offset), it is necessary to check the influence of lateral variation. In order to test this aspect, azimuthal soundings (according to the four cardinal points) were carried out. The results fall within the limits which are obtained from the equivalence principles. Therefore, the assumption of local horizontal layering is justified in the frame of the layout employed here.

### 3.2. INTERPRETATION METHODS

Both electrical soundings and TDEM surveys were interpreted by using the SELMA software (Christensen and Auken, 1992; Christensen and Jacobsen, 1999).

For each separate method the data set is interpreted in a standard 1D scheme. Models with a minimum number of layers for TDEM soundings were chosen to fit the shape of the apparent resistivity curves. The resultant solution however is not unique, because of the principles of suppression and equivalence (Koefoed, 1979). For electrical soundings, the same number of layers was taken to facilitate the comparison.

The SELMA software implements a standard non-linear inversion scheme (Mencke, 1984), incorporating *a priori* information via a covariance matrix  $C_m$  model. The increment  $\overline{\Delta x}$  of the parameter vector is derived from the difference  $\overline{\Delta y}$  between observed and calculated data by the equation:

$$\overline{\Delta x} = [A^T C_e^{-1} A + C_m^{-1}]^{-1} A^T C_e^{-1} \overline{\Delta y}$$

where  $A$  the Jacobian matrix;  $C_e$  the diagonal covariance matrix (the data error covariance);  $C_m$  a non-diagonal matrix (covariance matrix model).

The parameter vector includes layer thickness and resistivity, and an anisotropy factor (square root of the quotient between vertical and horizontal resistivities). The misfit function takes the standard form:

$$d^2 = \frac{1}{N} \sum_{i=1}^N \frac{(\rho_{a,i}^{\text{cal}} - \rho_{a,i}^{\text{meas}})^2}{\text{var}(\rho_{a,i}^{\text{meas}})}$$

where  $\rho_{a,i}^{\text{cal}}$  is the apparent resistivity calculated;  $\rho_{a,i}^{\text{meas}}$  is the apparent resistivity measured;  $\text{var}(\rho_{a,i}^{\text{meas}})$  is the variance of  $\rho_{a,i}^{\text{meas}}$ ;  $N$  is the number of resistivity data.

The user can choose a maximum number of steps and a minimum for the relative change in residuals (differences between data and responses). If one of these

two limits is reached the programme stops. This software allows to carry out both separate and joint inversion. Following Jupp and Vozoff (1975), who have applied the joint inversion to magnetotelluric and DC data, we put together in the same data vector DC and TDEM data. Using the same user-defined model the inversion program is run and the residuals of the entire data set are estimated at each iteration.

For a comparison between the results of separate and joint inversion, five representative sounding points were taken into consideration. The association of electrical sounding and TDEM measurement was made considering the position of the TDEM transmitter coil centre that differs from the electrical sounding point about  $\pm 0.5$  m.

## 4. Electrical and TDEM Separate Inversion

### 4.1. TDEM DATA

The PROTEM records data at twenty different times. As a result, each sounding is in theory composed of twenty data points. Nevertheless, the sounding presented hereafter (Figure 4) has only twelve of them. This is due to the fact that the background noise prevails from the record 13 to 20. Thus, Figure 4 represents the twelve apparent resistivities of sounding TDEM no. 5, compared with those obtained from a deterministic modelling. The selected model minimises the number of layers necessary for the data fitting. In this precise case, this number is four, but it can vary from one sounding to another according to the moisture state of the first decimetres of the earthflow.

We note that the curve is very well fitted, except for the points 1, 2 and 12. On these points cannot be modelled properly. Concerning the first two points, two possibilities exist: the noise affecting the data or the software. First of all, the software SELMA does not take into account the bandwidth of the receiver coil. This can have an influence on the first record but it could not be evaluated. Furthermore, the induced polarisation effect (IP) was evaluated. It is possible to account for this effect through modelling. We measured the IP effect on ten samples taken on the same vertical between 0 and 6 m depth. For the whole set of samples, the maximum effect of induced polarisation is 40 milliradians. Correcting for this effect using a model reveals a difference of only 1%. These explanations might be not sufficient to eliminate the misfitting, but this will not alter the significance of results.

We also note that the resistivity strongly increases at the end of the curve. Perhaps this might explain the difficulty to model record no. 12. In order to obtain a mathematical and geologically correct model it is necessary to supply a semi-fixed depth value in the *a priori* model, which was allowed to vary within 20–30% range. Otherwise no realistic model can be given. The model obtained is the following:

- 14  $\Omega$  m for the first layer over 3 m thickness,
- 7  $\Omega$  m for the second over approximately 1 m,

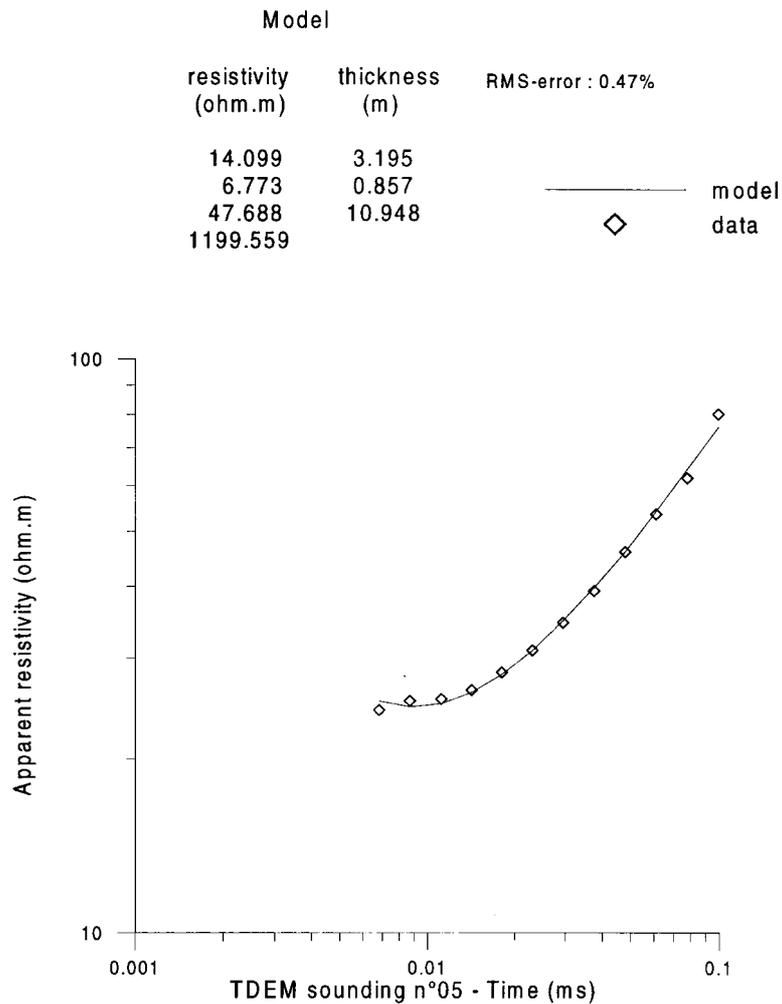


Figure 4. TDEM data inversion: example of td05 located in the eastern part of the earthflow (see Figure 7 for location).

- 48  $\Omega$  m for the third over 11 m,
- over 1000  $\Omega$  m for the last layer.

This last value is not realistic for a marl formation whatever the rock alteration state. Nevertheless, the measured resistivity values also depend on the applied method. The TDEM, being sensitive to the conductors defines poorly the resistant layers, in particular when the resistivities increase. For this example, the RMS-error is only 0.47%, but some a priori information was needed to fit the data.

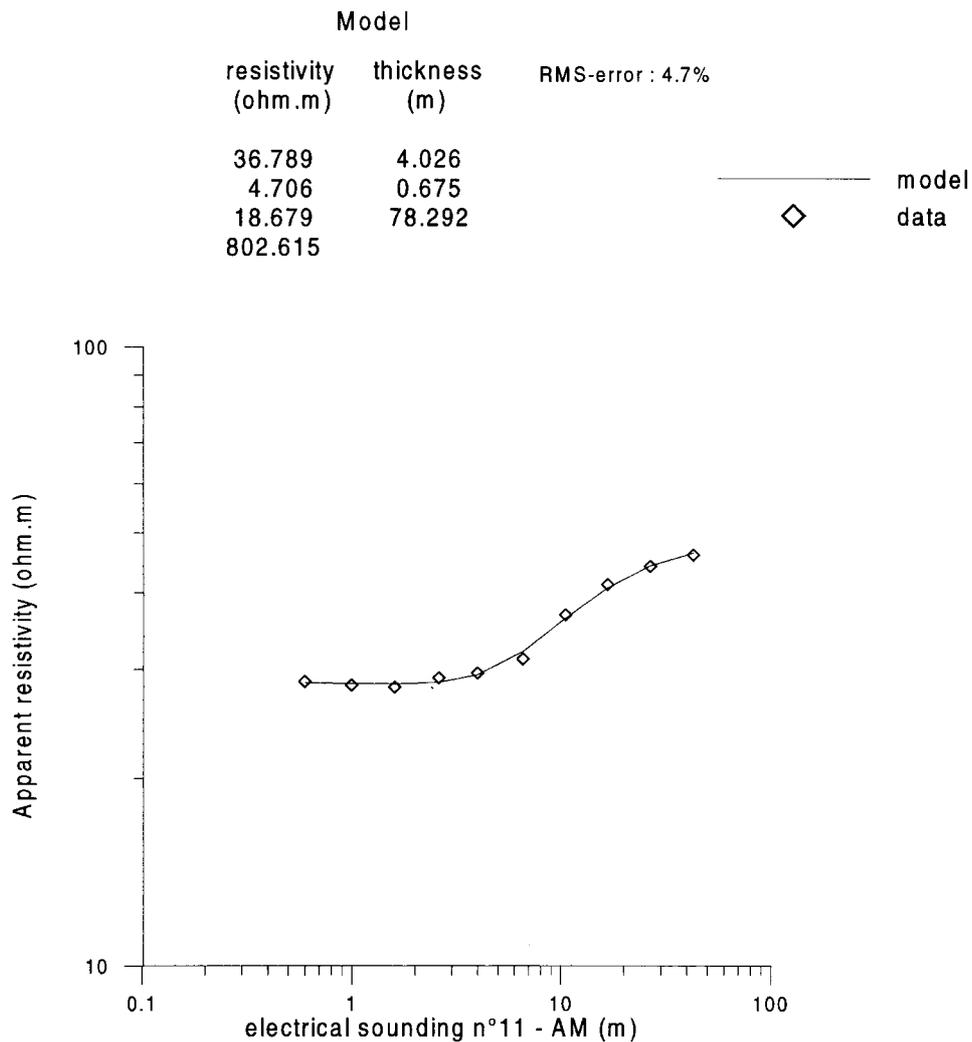


Figure 5. Electrical data inversion: example of e11 located in the eastern part of the earthflow (see Figure 7 for location).

#### 4.2. ELECTRICAL DATA

Figure 5 shows the apparent resistivities of the electrical sounding no. 11, as well as a deterministic model. The selected model uses the same number of layers that for TDEM inversion.

The inversion correctly fits the mathematical model whether we fix the substratum depth in the a priori model or not. But a geologically correct model is obtained only by fixing the substratum depth. If not fixed, the estimated thickness is unrealistic (about 100 or 200 m depth). Then by fixing the substratum depth, the RMS-error is 4.7% and the resistivity progression is the following one: the first

layer has a resistivity of approximately 40  $\Omega$  m, the second of approximately 4–5  $\Omega$  m, the third of 20  $\Omega$  m and the last is about 800  $\Omega$  m (Figure 5).

Our analysis shows that the two separate inversions yield different models for the same location. Moreover, a geologically correct model can only be obtained by fixing the depth of the substratum. Taking into account the differences of the results, the different sensitivity of the two methods, their complementarity and the necessity to introduce the substratum depth into the *a priori* model to obtain realistic results, joint interpretation is essential.

## 5. Joint Inversion

Joint interpretation is presented in two steps: the first one concerns only one TDEM-electrical sounding pair. The second one considers a part of profile C (Figure 3) with five geophysical sounding pairs between the CEP2 and CPZ1 drillings. The drillings allow us to compare and validate the results. Our interpretation of the drillings differs from that of Genet and Malet (1997) taking into account that the limit between the earthflow and the substratum is not necessary obvious.

### 5.1. JOINED INTERPRETATION OF ONE ELECTRICAL-TDEM SOUNDING PAIR

Because of the complexity of the site and the difference in sensitivity of the methods, the best fit of a model to the electric data and TDEM can only be obtained by:

- increasing the number of layers of the model (from 4–5 to 6–7),
- allowing the anisotropy of each layer to vary.

The SELMA software is the only package we know that accounts for anisotropy effects. By default the anisotropy is fixed at 1, but it is possible to let it vary. Knowing that without this possibility any mathematically and geologically correct inversion is impossible for our site, the capacity to let vary the anisotropic factor in the software is of great value. In addition, the fact of having an anisotropy different from 1 is easily justified for this heterogeneous flow. The result of the optimal joint interpretation of the surveys studied above is shown in Figure 6. This result was obtained by introducing six layers and by varying all the parameters (resistivity, thickness, depth and anisotropy). A good agreement of the inverted model with the electrical and TDEM data is observed. As for separate TDEM inversion, the first two points are not well predicted by the model. However, contrary to the separate inversions the last two electrical points are slightly shifted compared to the model prediction.

The possible explanation for the misfit of the last TDEM point was given in Section 4.1. The shift of the last two electrical points can be explained by the effects of lateral variation which increases with distance, keeping in mind that the earthflow mass has a large thickness variability (from 0 to 20 m approximately).

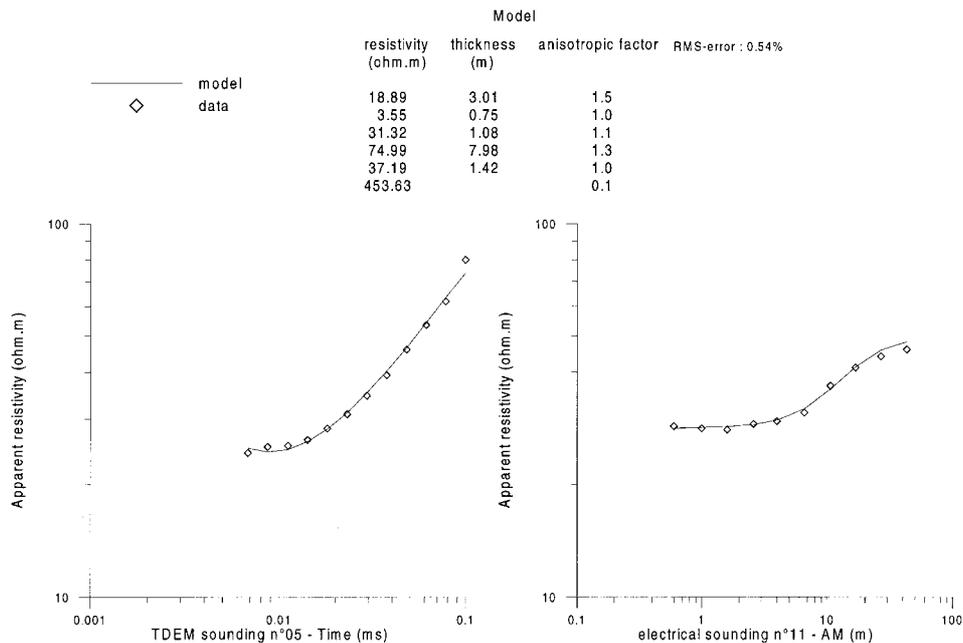


Figure 6. Electrical-TDEM data joint inversion: example of el11 and td05 (see Figure 7 for location).

The RMS-error is only 0.54%: this is almost the same value obtained for TDEM separate inversion, but here no a priori information was needed.

The resulting model thus consists of six layers whose characteristics are given in Figure 6. The factors of anisotropy of the various layers range between 0.98 and 1.5, except for the substratum for which a value of 0.1 was found. Although the substratum is probably less anisotropic, its value is surprising and remains unexplained. However, the other values are acceptable considering the studied soil. The general scheme consists of an alternation of conducting and resisting layers. The first layer has a resistivity of about 20  $\Omega$  m and a thickness of 3 m. Underneath, there is the most conducting layer with 3.5  $\Omega$  m and a thickness of 0.7 m. The presence of such a layer is mainly supported by the TDEM data, which pointed out it also in the separate inversion, the TDEM being particularly sensitive to the conducting layers. This layer is followed by another thin layer (1 m) with resistivities of about 30  $\Omega$  m. The fourth layer has a thickness of 8 m and resistivities of 75  $\Omega$  m, the fifth is about 1.4 m for 37  $\Omega$  m. The last layer has the highest resistivity: 450  $\Omega$  m. This high value suggests that the substratum has been reached. According to the results of the joint inversion, the substratum is found at a depth of about 14 m without fixing any parameter into the a priori model. Considering that the depth of the substratum determined by the drilling CEP2 was 15.2, the agreement with the results obtained from the joint inversion appears very good.

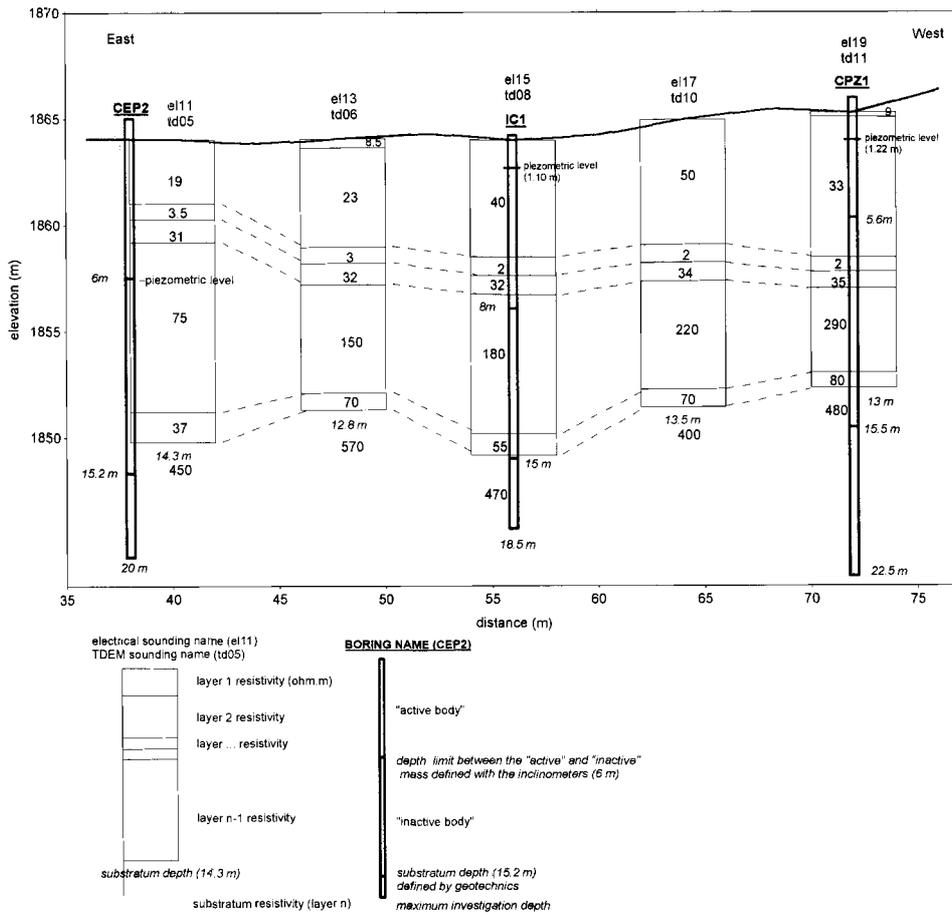


Figure 7. Joint interpretation of 5 electrical-TDEM sounding pairs and comparison with geotechnical reinterpretation (see Figure 2 for location).

### 5.2. JOINED INVERSION ON FIVE ELECTRICAL-TDEM SOUNDING PAIRS

The excellent fitting shown above is obtained for almost all of the inversions carried out, except for the electrical-TDEM pair of soundings el15 and td08 which are located near drilling IC1 (Figure 3). This drilling indicates that the substratum basis is located at about 16 m depth. Thus, we fixed the depth to 15 m in the *a priori* model and allowed a variation of 20%, which enables us to include all the geotechnically possible solutions. Figure 7 summarises in log-form the results of the five electrical-TDEM sounding pairs, and Table I the characteristics of the internal structure of the earthflow. It also indicates the most probable depths of the substratum determined from three drillings. Several remarks can be made:

(a) With the joint inversion technique, the substratum depth can be accurately estimated without supplying *a priori* information. This is not possible with the

TABLE I  
Characteristics of the joint inversion six layer model

Layer	Thickness range (m)	Resistivity range ( $\Omega$ m)	Anisotropic factor range	Comments
1	3–6.6	19–50	0.6–1.7	Active unit
2	0.7–0.9	2–3	0.35–1	Wet transition layer
3	0.7–0.9	31–35	0.9–1	Top of the inactive unit
4	4–8	150–290	0.35–1.33	Inactive unit
5	0.7–1.4	37–80	0.7–1	Transition between inactive unit and substratum
6	/	400–570	0.1	Substratum

separate inversions of the soundings. The measured depths of the substratum are consistent with the estimated range of values. The observed differences between the two methods never exceed 3 m and could be explained as follows. The substratum was defined in the geotechnical investigation as the medium where the rate of penetration of the stem train was smaller than about 10 m/h. This value is based on experiments and literature, but may be questionable (Genet and Malet, 1997; Flageollet et al., 1996).

Taking into account the uncertainty of the substratum depth estimation for both methods (geophysical and geotechnical) and the difference in the physical properties of the parameters characterising the soil (electrical resistivity on one hand, compactness on the other hand), small discrepancies are not surprising.

(b) a “6 layer” model appears appropriate for all soundings, except for the second (e113 and td06) and the fifth one (e119 and td11 in Figure 7) which require a very thin additional superficial layer with low resistivities of approximately 9  $\Omega$  m. The presence of this layer can be explained by the large surface heterogeneity which strongly influences the resistivity of the first decimetres of the soil.

This six layer geophysical model needs to be analysed and compared with the three layer geotechnical model: this consists of an earthflow, including an active unit superposed to an “inactive unit”, which covers the impermeable marly substratum. The various anisotropic factor values of the different layers can be a consequence of the effect of soil compactness on the electrical conductivity.

The integrated geophysical and geotechnical interpretation of the six layer model is as follows:

- the first layer could correspond to the active unit (very active and wet viscous mud formation): the resistivities of this layer are comprised between 19 and 50  $\Omega$  m, increasing with thickness. As expected, the thickness increases from 3 to 6.6 m, from the east to the centre of the earthflow. The anisotropic factor range is from 0.9 to 1.7;

- the thin second layer (0.7–0.9 m), with very low and constant resistivities (2–3  $\Omega$  m) and with anisotropic factors between 0.35 and 1, could correspond to a very wet transition layer. Even if geotechnical results do not show the presence of this layer, at this depth they show a limit between two physically different masses. The limit could be marked by a transition zone that geophysically appears as a distinct layer. Since the inactive unit underlies this layer, the observed very low resistivities could be connected to a high water content, and/or to an accumulation of clays and/or metal minerals. Since the last possibility can be excluded on the basis of the results of IP measurements carried out on soil samples, thus, the most likely explanation is a high water content. This assumption is supported by the fact that very low values of resistivities (3–5  $\Omega$  m) are measured in presence of water both in the gullies and in the piezometric tubes;
- the third thin layer (0.7–0.9 m thickness) with resistivities ranging between 31 and 35  $\Omega$  m could correspond to the top of the inactive unit, whose first decimetres are compacted. This phenomenon can sometimes be observed on slip surfaces (in our case, the occurrence of this layer could be due to the faster flow of the overlying layer). The average anisotropic factor is about 0.9-1, even if the value for the electrical-TDEM 15-08 sounding pair is equal to 4.
- the fourth layer corresponds well to the inactive unit geotechnically described by Flageollet et al. (2000). This lower unit is a stiff compact and stable formation (impervious material and dry conditions). Its thickness varies from 4 m (to the west) to 8 m (to the east). Its resistance defined geotechnically (resistance of the rod > 10 Mpa), is on average higher than that of the other layers (< 10 Mpa), although the layer reveals variations in compactness. The resistivities range between 150 and 290  $\Omega$  m, except for the el11-td05 sounding pair whose resistivity of 75  $\Omega$  m indicates a lower compactness towards the eastern boundary of the earthflow. The anisotropic factor varies between 0.35 and 1.33. The variations could also be the consequence of the effect of soil compactness on the electrical conductivity.
- the fifth layer is thin (0.7–1.4 m) and its resistivity ranges from 37 to 80  $\Omega$  m while the anisotropic factor ranges from 0.7 to 1. This layer could correspond to a transition layer between the inactive body and the in-situ marls. Indeed, its resistivities are lower than those of the substratum, indicating a lower original compactness. This layer could correspond to the stony surface which covered the gullies before the earthflow occurred. This phenomenon can be observed in the gullies of the present-day torrential basin. As an alternative, this layer could also correspond to an in-situ black marls alteration zone.
- the substratum (sixth layer of the model) has resistivities ranging from 400 to 570  $\Omega$  m and an anisotropic factor of 0.1. Measuring the resistivity of a formation, the result depends on many factors including the applied measuring method. Therefore, electrical and TDEM resistivities can show discrepancies. Moreover, considering the limited extension of the electrical array in this study,

the substratum characteristics can not be reliably assessed using electrical method. Thus, the TDEM appears to be a more suitable method for the detection of the substratum, even though this method does not well define its resistivity. This problem is overcome by applying the joint inversion of both methods. This once again shows the advantage of the joint inversion, which proved to be an excellent tool to study soil stratification on such heterogeneous materials.

## 6. Conclusions

Through the study of five sounding pairs, this paper highlights the considerable advantage of the joint inversion of electrical and TDEM data compared to the separate inversions. The dissociated inversions carried out in a deterministic scheme do not provide an accurate image of the structure. A priori information plays a crucial role in constraining the models due to non-unique solutions in electrical and TDEM data interpretation. Their joint inversion provides a more detailed and well-constrained solution, benefiting from the differences in sensitivity of each method. Despite the unfavourable context (rough topography, large lateral heterogeneities), joint 1D inversion seems to be a suitable technique to study the 3-D structure of a site. The six (or seven) layer model obtained from the joint inversion is satisfactory because it is consistent with the available geological and geotechnical information. Furthermore it is possible to detect the geotechnical limits such as the substratum and the transition zone between the active and the inactive body.

However, a good fitting model could only be obtained by allowing for variation in anisotropy. The resulting range in the values of the anisotropic factors is from 0.1 to 1.7 for the all considered layers (except for one layer of one sounding) of the various inversions. The question arises about the physical meaning of this variability. Possibly, the variation in anisotropy reflects compactness variations due to the earthflow dynamics and evolution.

## Acknowledgements

This research has been carried out with the financial support of the CNRS in the framework of the PNRN (Programme National Risques Naturels, Contract PNRN 98-34MT, Contribution number 197). Many thanks to J.P. Malet for preparing Figures 1 and 3.

## References

- Archie, G.: 1942, 'The electric resistivity log as an aid in determining some reservoir characteristics', *Trans. Am. Inst. Mech. Eng.* **146**, 54–62.

- Bredewout, J.W., Poort, J.A., Meekes, J.A.C. and van Overmeeren, R.A.: 1996, 'Joint inversion of VES and TEM data; success and failure', *Environmental and Engineering Geophysical Society*, Nantes, pp. 773–776.
- Christensen, N.B. and Auken, E.: 1992, 'SELMA-Simultaneous Electromagnetic Layered Model Analysis', in B.H. Jacobsen (ed.), *Proceedings of Interdisciplinary Inversion Workshop 1*, Geoskripter, Aarhus University, 41, pp. 49–56.
- Christensen, N.B. and Jacobsen, B.H.: 1999, 'The SELMA manual Version May 1999', Aarhus University.
- Colas, G. and Locat, J.: 1993, 'Glissement et coulée de La Valette dans les Alpes de Haute-Provence. Présentation générale et modélisation de la coulée', *Bulletin Liaison du Laboratoire des Ponts et Chaussées*, **187**, 19–28.
- Dikau, R., Brunsten D., Schrott, L. and Ibsen, M.-L.: 1996, *Landslide recognition/identification, movement and causes*, Wiley, 251 p.
- Eckard, M.H., Hanstein, T.H.K. and Strack, K.M.: 1994, 'Joint inversion of transient electromagnetic and direct current measurements', *European Association of Engineers and Geoscientists – 56th Meeting and Technical Exhibition*, Vienne, Austria, 6–10 June.
- Flageollet, J.C.: 1988, *Les mouvements de terrain*, Masson, 224 p.
- Flageollet, J.C., Maquaire, O. and Weber, D.: 1996, 'Geotechnical investigations into the Super Sauze landslide. Geomorphological and hydrogeological results', In: Workshop: "Landslides and Flash flood", Centre Européen sur les Risques Géomorphologiques, Barcelonnette – Vaison la Romaine du 30-9 au 3-10, pp. 30–38.
- Flageollet, J.C., Maquaire, O., Martin, B. and Weber, D.: 1999, 'Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern Alps, France)', *Geomorphology*, pp. 68–78.
- Flageollet, J.C., Malet, J.P. and Maquaire, O.: 2000, 'The 3D structure of the Super Sauze flowslide: a first stage towards its behaviour modelling', *Phys. and Chem. Of the Earth (B); European Geophysical Society Journal*, **25**(9), 785–791.
- Genet, J. and Malet, J.-P.: 1997, 'Détermination de la structure tridimensionnelle du glissement de Super Sauze par une investigation géotechnique', Mémoire de maîtrise de Géographie Physique de l'Université Louis Pasteur de Strasbourg, 138 p + annexes.
- Julian, M. and Martin, J.: 1982, 'Risques naturels et catastrophes', *Bulletin de l'Association des Géographes Français*, Paris, no. 485–486, pp. 295–304.
- Jupp, D.L.B. and Vozoff, K.: 1975, 'Stable iterative methods for the inversion of geophysical data', *Geophys. J. Roy. Astr. Soc.* **42**, 957–976.
- Keefer, D.K. and Johnson, A.M.: 1983, 'Earth flows: morphology mobilisation and movement', *Geol. Surv. Prof. Paper* 1264, US Govern. Print. Off. Washington.
- Koefoed, O.: 1979, *Geosounding principles, 1, Methods in Geochemistry and Geophysics, 14 A*, Elsevier, Amsterdam.
- Kunetz, G.: 1966, *Principles of direct current resistivity prospecting*, Geopublications Associates, Geoexploration Monographs.
- Malet, J.P., Maquaire, O. and Klotz, S.: 2000, 'The super-Sauze flowslide (Alpes-de-Haute-Provence, France). Triggering mechanisms and behaviour', *8th Int. Symp. on Landslides*, Cardiff, Wales, 26–30 June 2000, **2**, 999–1004.
- Malet, J.-P., Hartig, S., Calais, E. and Maquaire, O.: 2000, 'Apport du GPS au suivi en continu des mouvements de terrain. Application au glissement-coulée de Super-Sauze (Alpes-de-Haute-Provence, France)', *C.R. Acad. Sci. Paris, sér. IIa.*, **331**, 175–182.
- McNeill, J.D.: 1994, 'Principles and application of time domain electromagnetic techniques for resistivity sounding', Technical Note TN-27, Geonics.
- Mencke, W.: 1984, *Geophysical data analysis: discrete inverse theory*, Academic Press Inc.
- Nabighian, M.N. and MacNae, J.C.: 1991, 'Time domain electromagnetic prospecting methods', in M.N. Nabighian (ed.), *Electromagnetic methods in applied geophysics*, Vol. 2: Applications, Chapter 6, *Soc. Expl. Geophys. publication*, pp. 427–520.

- Palmer, D.F. and Weisgarber, S.L.: 1988, 'Geophysical survey of the Stumpy Basin Landslide, Ohio', *Bulletin of the Association of Engineering Geologists* **25**(3), 363–370.
- Raiche, A.P., Jupp, D.L.B., Rutter, H. and Vozoff, K.: 1985, 'The use of coincident loop transient electromagnetic and Schlumberger sounding to resolve layered structures', *Geophysics* **50**, 1618–1627.
- Reynolds, J.M.: 1997, *An introduction to applied and environmental geophysics*, Wiley.
- Schmutz, M.: 2000, 'Apport des méthodes géophysiques à la connaissance des glissements-coulées développées dans les marnes noires. Application à la coulée de Super Sauze (Alpes de Haute Provence, France)', Thèse de l'Université Louis Pasteur de Strasbourg, 231 p + annexes.
- Schmutz, M., Guérin, R., Maquaire, O., Descloîtres, M., Schott, J.J. and Albouy, Y.: 1999, 'Contribution of a combined TDEM and electrical survey to the investigation of the Super Sauze flowslide internal structure', *C.R. Acad. Sci. Paris, Ila* **328**, 797–800.
- Vozoff, K. and Jupp, D.L.B.: 1975, 'Joint inversion of geophysical data', *Geophysics Journal of the Royal Astronomical Society* **42**, 977–991.
- Weber, D. and Herrmann, A., 2000, 'Contribution de la photogrammétrie numérique. l'étude spatio-temporelle de versants instables: l'exemple du glissement de terrain de Super-Sauze (Alpes de Haute-Provence, France)', in *Bulletin de la Société Géologique de France* (in press).
- Zhang, X., Phillips, C. and Marden, M.: 1991, 'Internal deformation of a fast-moving earthflow, Raukumara Peninsula, New Zealand', *Geomorphology* **4**, 145–154.