Landslide characterization by RMT and VLF-EM geophysical survey and continuous groundwater monitoring

Caractérisation d'un glissement de terrain par campagne géophysique RMT et VLF-EM et par auscultation hydrogéologique en continu

Ch.Bonnard – *Laboratory of Soil Mechanics, EPFL, 1015 Lausanne, Switzerland*
F.Bossy – *Hydrogeology Centre, UNINE, 2000 Neuchâtel, Switzerland*
F.Noverraz – *Karakas & Français SA, 1000 Lausanne, Switzerland*

ABSTRACT: In order to determine precisely the spatial geometry of the slip surface of a fairly shallow slide, a geophysical survey has been carried out using RMT and VLF-EM electromagnetics techniques; they have allowed the description of the position, nature and structure of the bedrock below the landslide masses in all the extension of the unstable zone. Moreover continuous monitoring of the groundwater level was carried out in and below the landslide mass and put forward sudden pressure variations in the bedrock. These date were used to understand the equilibrium conditions of the landslide in typical and critical situations.

RÉSUMÉ: Afin de déterminer avec précision la géométrie de la surface de glissement sous une masse instable relativement peu profonde, une campagne de géophysique a été effectuée en utilisant des techniques électro-magnétiques RMT et VLF-EM; celles-ci ont permis de décrire la position, la nature et la structure du massif rocheux sous-jacent sur toute l'extension de la zone instable. De plus, l'auscultation en continu des conidtions hydrogéologiques a été conduite dans et sous la masse instable et a permis de mettre en évidence de soudaines variations de pression dans le massif rocheux sous-jacent. Ces données ont été utilisées pour comprendre les conditions d'équilibre du glissement de terrain dans certaines situations typiques ou critiques.

1 INTRODUCTION

In order to study the role of the forest cover on the activity of slides in Flysch formations, and in particular on a fairly shallow slide at Creux d'Enfer, in the Gérine valley of the Canton of Fribourg, Switzerland (see location in Figure 1), at an altitude of some 1'500 m, a detailed investigation has been recently carried out by the Soil Mechanics Laboratory of the Swiss Federal Institute of Technology of Lausanne (EPFL), on behalf of the Federal Direction of Forests. It was necessary to know precisely the spatial geometry of the slip surface, with more details than on the basis of the two boreholes carried out (TO1 or TO2, as shown on Figure 1), as well as to assess the timely variability of groundwater conditions in the landslide mass and below the slip surface, in the Flysch formation.

Therefore, after defining a first approximate geometry of the slip surface by borehole results and a geological interpretation, and as the inclinometer measurements did not show yet significant displacements, two different geophysical campaigns were led by the Hydrogeology Centre of Neuchâtel University (UNINE), using new electromagnetic RMT and VLF-EM techniques.

Furthermore, several sensors were installed in the main boreholes as well as in adjacent drillholes in order to record the groundwater pressure fluctuations during more than one year, partly as continuous data, partly as discrete information.

All these data provide significant facts which allow a better understanding of the landslide intrinsic conditions, in relation with the effect of the forest cover, as well as a good opportunity to test new investigation methods in an interdisciplinary framework.

2 GEOLOGICAL CONDITIONS OF THE LANDSLIDE SITE

The small valley of Creux d'Enfer (literally "Hell hole") is cut in the Gurnigel Flysch, here of medium Eocene age. This formation, according to the fairly scarce outcrops in the region, includes a higher proportion of plated marls with some fine sandstone and limestone layers.

The dip of the layers is oriented N-E with a deep plunging below the crest bordering the valley where the layers are nearly in dipslope (see lower part of Figure 1, beside the legend). This dip reappears at the lower part of the slide with an inclination of 20 to 25°, but changes in direction on the other side of the river flowing at the toe of the slope, with a S-E orientation. There is thus a folded structure in the shape of a small syncline.

The dip of the Flysch rock layers has thus a relation with the slip surface only in the upper part of the slope, within the scarp in which dip slope conditions prevail. Below, the dip is steeper than the slip surface so that the layers intersect it.

Then a local morainic cover appears, as it is visible in borehole TO2, which separates the sliding mass from the Flysch bedrock. It is not possible to determine at the moment if this morainic cover is slidden or in place.

The Creux d'Enfer slide covers an area of some 0.3 km^2. It is divided into several topographically and mechanically independent parts. The studied part is the eastern one, which seems to be more active. It has a length of 500 m and an average width of 250 m (see Figure 1, in which the upper more active part is drawn).

Downstream, the Creux d'Enfer river flows on the bedrock, so that the toe of the slide is not eroded anymore, even if it develops on an increasing slope. The central part of the slide displays on the contrary a low inclination, which may explain the temporary absence of movements as presently measured. Only in the scarp zone some local signs of activity are visible (fresh scars) but in general the cracks and fissures of the ground and on the forest road are not outstanding.

3 GEOPHYSICAL INVESTIGATIONS

Two different electromagnetic methods were used at the "Creux d'Enfer" site, radio magnetotellurics (RMT) and very low frequency – electromagnetics (VLF-EM) (Turberg et al., 1993; Turberg, 1994). Both of these methods were developed at the University of Neuchâtel and can be used to indirectly evaluate the geometry and the structure of the landslide and its substratum. They are particularly well-adapted to landslide studies where the topographic conditions and vegetation may hinder the use of other methods. Only two people are required to manipu-

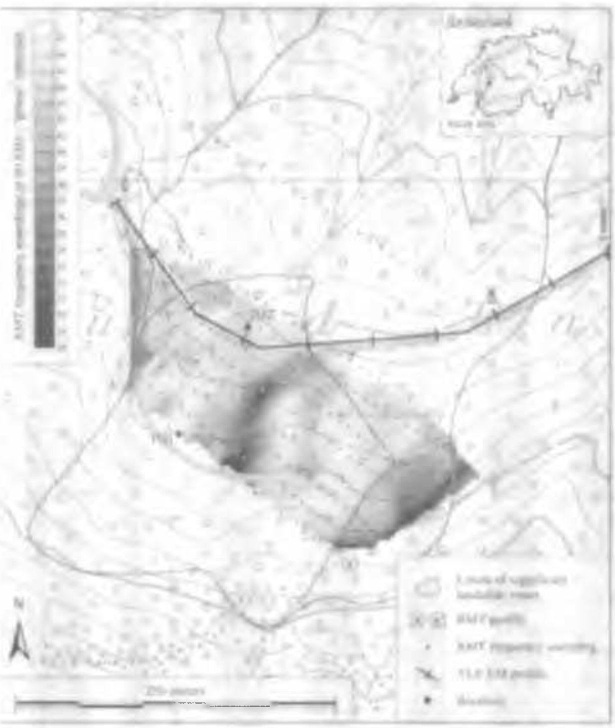

Figure 1. "Creux d'Enfer" landslide showing the location of electromagnetic measurements obtained using *Radio MagnetoTellurics* and *Very Low Frequency – ElectroMagnetics* methods. A map of phase values determined from the RMT soundings at 60 KHz is superimposed on these data (see corresponding scale)

late the instruments. This allows many measurements to be made under otherwise awkward conditions (rugged topography, forest cover).

3.1 *RMT investigations*

RMT method is based on the properties of electromagnetic waves in the low and very low frequency ranges (12-240 KHz) emitted from long distance radio transmitters around the world. Using this method, it is possible to measure the apparent resistivity of the subsoil. Signals measured at various frequencies allow the resistivity of various layers underlying a location to be determined.

For each frequency F (Hz), the transmitted waves generate a variation of the earth primary magnetic field that induces electrical currents in the soil. The circulation of these electrical currents produces a secondary magnetic field that alters the primary field. RMT measures these electrical currents $\boldsymbol{E}$ ($V{\cdot}m^{-1}$) and resultant magnetic fields $\boldsymbol{B}$ ($A{\cdot}m^{-1}$). The magnitude of $\boldsymbol{E}$ and $\boldsymbol{B}$ depends on the nature of the soils under investigation and allows their apparent resistivity $\boldsymbol{Ra}$ ($\Omega{\cdot}m$) to be calculated using the following formula (see Equation 1) :

$$Ra = \left(\frac{E}{B}\right)^2 \cdot \frac{1}{2\pi F \mu_0} \quad \text{where} \quad \mu_0 = 4\pi \cdot 10^{-7}\ (\mathrm{H{\cdot}m^{-1}}) \qquad (1)$$

To carry out a vertical resistivity sounding at a point, measurements are made at several decreasing frequencies. The lower the frequency selected, the greater the skin depth (depth of investigation). The skin depth $\boldsymbol{P}$ (m) is calculated using the following formula (see Equation 2) :

$$P = 503 \cdot \sqrt{Ra / F} \qquad (2)$$

In the field, electrical currents are measured by two electrodes spaced 5 m apart and the magnetic field measured with a directional antenna. Furthermore the RMT device directly provides the operator with a resistivity value for each frequency under consideration. In addition, the phase difference between the electric and magnetic field is also measured. The phase difference provides information on the sequence of conductive and resistant lithologies underlying a sounding location. In a homogenous formation, the value of the phase difference will be 45°. If a conductive formation overlies a resistant formation, then the phase difference will be less than 45°. When the phase is more than 45°, a resistant formation overlies a conductive unit. 1D magnetotelluric-inversion methods can simulate the resistivity and phase values in order to obtain a stratigraphic picture of the underlying deposits (Raetzo et al., 1995).

At the "Creux d'Enfer" site 259 RMT soundings organized in 9 profiles were carried out over 3 days (see locations on Figure 1). Four investigation frequencies were chosen : 234, 183, 60 and 16 KHz. The resistivities and phases of the data were first treated by interpolation methods. This allowed different distribution maps of these parameters to be developed. During a subsequent interpretation phase, the data were modeled in order to demonstrate the landslide thickness for each sounding.

The 60 KHz phase distribution map is presented in Figure 1. The map shows a significant and interesting variation in phase values of about 20°. The low values appear at the NW and SE ends of the investigated zone and across the central part (darker zones on the map). The ends correspond approximately to the lateral landslide boundaries. The low phases (<< 45°) are due to a decrease in the landslide thickness. In fact, when the landslide thickness is sufficiently thin, the RMT method can detect the underlying Flysch formation, which is composed of an alternating sequence of sandstone beds separated by layers of marl. The resistivity contrast between the conductive landslide mass and the resistant Flysch is sufficiently large to yield an important phase difference of less than 45°. In the central part of the landslide, the situation was suspected to be similar.

The low phases are due to a rise in the underlying Flysch formation and a corresponding decrease thickness of the landslide mass. Analyses of the resistivity and phase values in this zone indicate the presence of sandstones at a shallow depth. This sandstone threshold subdivides the landslide into two thicker lobes. Between the central zone and the margins, phases increase progressively until they reach values approaching 45° in the center of each lobe. This phenomenon is caused by a greater thickness of the conductive landslide mass. In this case, only the landslide mass is measured and the underlying more resistant Flysch sandstones cannot be detected.

Modelling of the 259 RMT soundings has permitted the Flysch formation to be characterized with resistivities of between 80 Ω·m (marls) and 600 Ω·m (sandstones). The landslide mass is rich in clay and marls and generally has resistivity values of between 20 and 80 Ω·m. Because of these resistivity differences, the depth of the Flysch formation has been determined with 1D magnetotelluric-inversion methods for more of the third of the 259 soundings. In other cases, the landslide mass is too thick or the resistivity contrasts between Flysch and landslide are insufficiently large to permit a distinction to be made.

Figure 2 shows a cross section of the landslide, A-A', drawn by using the results of the 24 RMT soundings. In this profile, half of the modeled measurements give a direct estimation of the Flysch depth. Other measurements provide a minimum depth to the top of Flysch. Moreover, borehole TO1 has allowed the depth to the top of Flysch to determined exactly. Where the Flysch was too deep to be determined, the top of this formation was arbitrary deduced from the skin depth at 16 KHz.

The processed data profile shown in Figure 2 further indicate that the landslide is subdivided into two parts. In fact, the sandstone threshold already displayed by the phase mapping at 60 KHz (see Figure 1) appears to be more significant than the raw data initially suggested. The decreasing thickness of the landslide mass toward these boundaries is also well illustrated by these data.

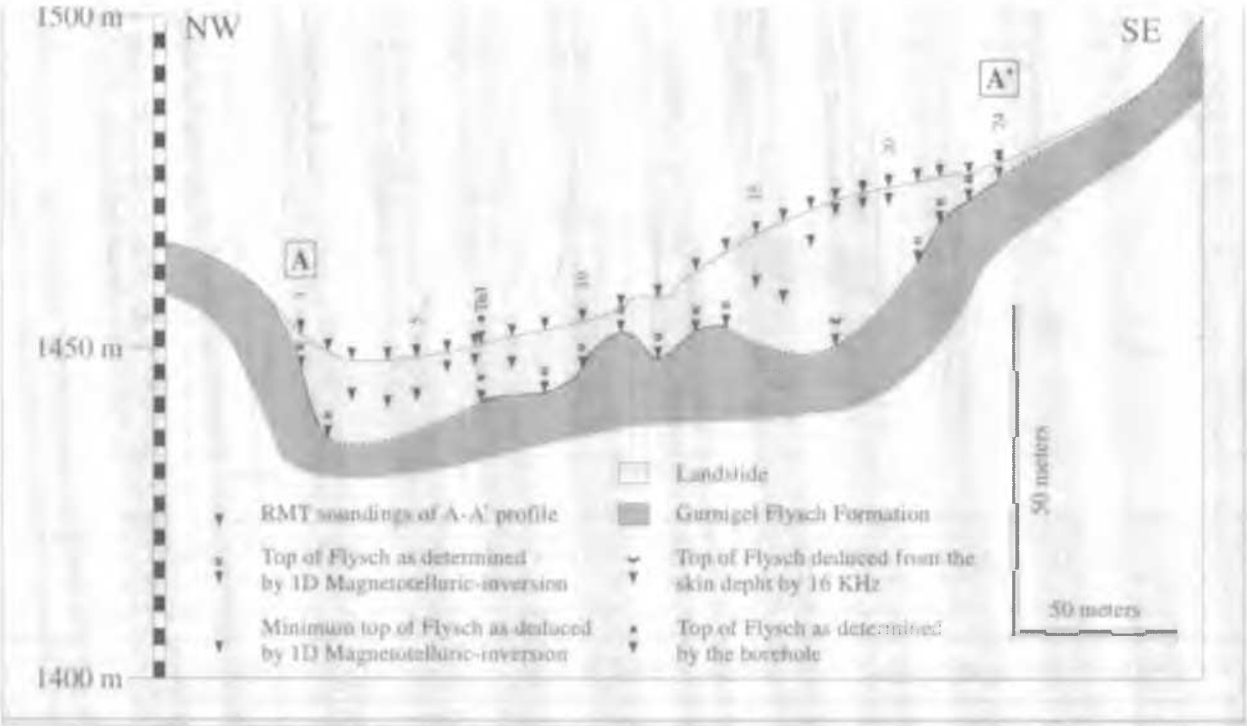

Figure 2. Landslide A-A' cross section obtained using 24 surface RMT soundings.

3.2 *VLF-EM Investigations*

The VLF-EM method is based on the same electromagnetic phenomenon as the RMT. The principal use of the method is to identify conductive structures in the ground, for example faults in the substratum. Applications at other landslide sites in Switzerland have demonstrated its use in detecting the unstable zone boundaries (Raetzo et al., 1995; Stiefelhagen, 1998).

VLF-EM apparatus measures induction parameters. In fact, two phenomena define the secondary magnetic field : a magnetic component, that is in-phase with the primary field, and a component, that is out-of-phase with the magnetic field. With the VLF-EM, only the outphase is measured. It is represented as a percentage of the primary field. Measurements are carried out continuously, without contact with the soil. Each abrupt variation of the signal indicates the presence of a discontinuity.

At the "Creux d'Enfer" site, an interesting VLF-EM profile was identified in the landslide (shown in Figure 1). The curve presented in Figure 3 shows the continuous evolution of the outphase parameter with the distance. An abrupt variation of the curve is notable at the distance of 410 m. This coincides exactly with the landslide western boundary. On the eastern boundary, the same phenomenon does not appear, probably because the profile direction is not perpendicular to the boundary. Moreover, the curve is very well structured with repetitive features.

Two alternating families of slopes occur between the maxima and minima of the curve. A secondary maximum appears each time in the rising part of the first slope family (see the circles in Figure 3). This curve structure is similar to VLF-EM results frequently obtained in soundings over fractured limestone. It is probably caused by the fractures in the Flysch or by the stratigraphic sequences characterizing this formation. Observations of surrounding Flysch outcrops support the fracture hypothesis as Flysch sandstones layers are very fractured at regular intervals.

The 16 KHz VLF-EM frequency used in this profile is apparently able to detect the Flysch substratum up to a depth of 20 m. The chaotic landslide mass does not seem to influence the results, otherwise the curve would not be so repetitive and structured.

4 GROUNDWATER MONITORING

Both investigation boreholes TO1 and TO2, in which inclinometer pipes have been installed, have also been equipped with several devices to monitor the groundwater pressures, namely a SINCO pressure cell at the bottom (at 12.5 m and 26 m deep respectively) and a Ø 10 mm micropiezometer with the entry zone at the same depth. Furthermore, two short additional boreholes TO3 and TO4 have been carried out in the immediate vicinity of TO1 and TO2 to determine the groundwater levels in the landslide mass by open piezometers, 3.7 m and 1.3 m deep respectively. Three of the piezometer sensors have been equipped with a continuous data acquisition system which was in operation during nearly two years.

The data continuously recorded from October 1998 to the end of July 2000 in boreholes TO1 and TO3 have revealed very interesting and contrasted hydrogeological conditions. As shown in

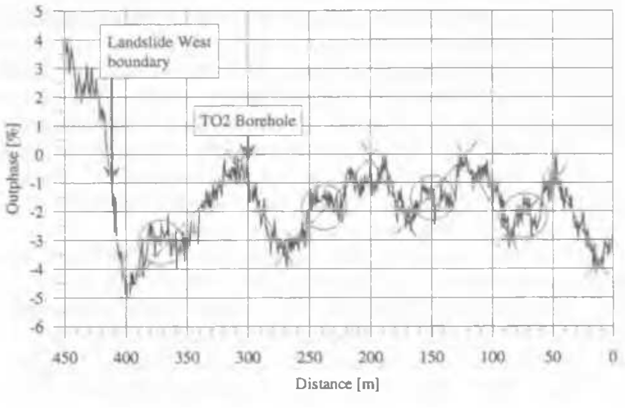

Figure 3. A VLF-EM profile continuously recorded across the landslide (see location in Figure 1). The abrupt variation at 410 m indicates the principal western landslide boundary. Lines and circles show the repetitive structures on the outphase curve. This pattern illustrates fractures or stratigraphic sequences in the Flysch Formation.

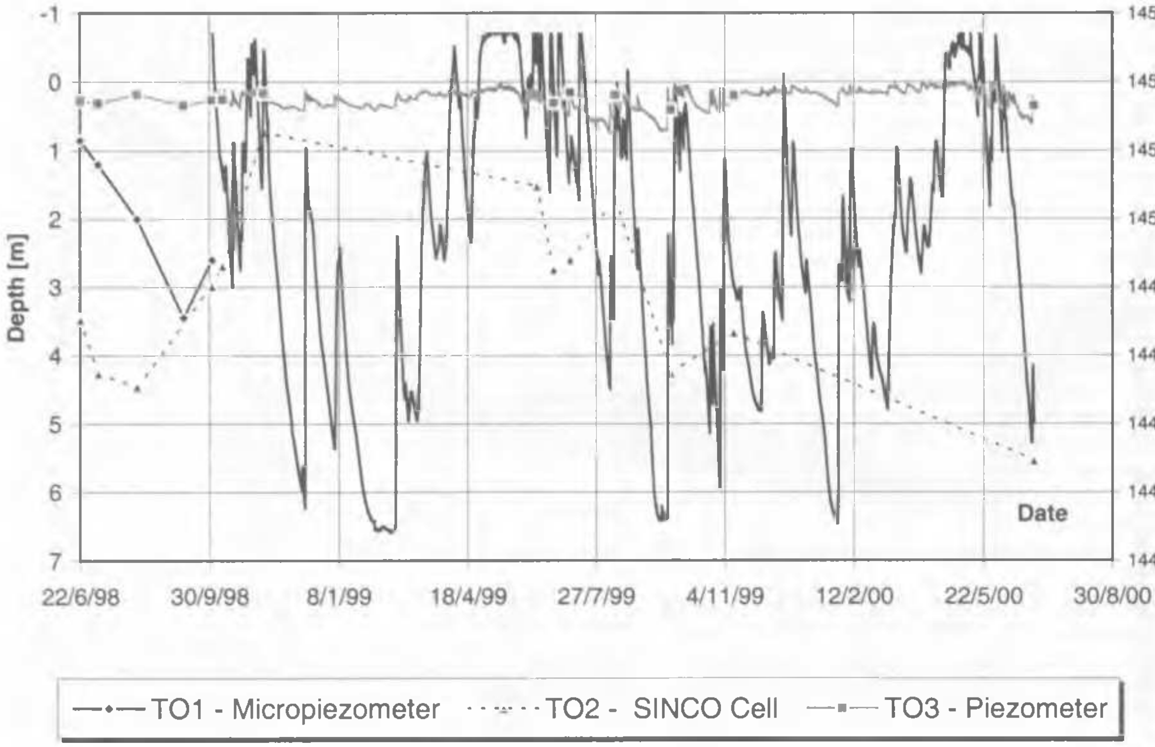

Figure 4. Fluctuations of groundwater pressures over 2 years in the upper part of the slide, showing a clear contrast between constant conditions in the landslide mass (TO3) and sharp variations in the Flysch bedrock (TO1)

Figure 4, the groundwater level within the landslide mass, recorded by TO3 piezometer, displays a very limited variation of some 0.6 m just below the ground level. During the snowmelt period, the groundwater level stays exactly at the ground level without any fluctuations, which proves that the landslide mass is saturated. Similar results are obtained by the discrete measurements in superficial piezometer TO4 which is adjacent to borehole TO2, in which the groundwater level stays nearly constantly at 0.8 m below the ground level, due to a local topographical effect induced by the fill of forest road (see Figure 1).

On the contrary the groundwater pressure in the Flysch bedrock below the sliding mass, at a depth of 11.5 m, displays most of the time sudden fluctuations which may reach an amplitude of some 7 m, as in November 1998 (see TO1 micropiezometer data in Figure 4). The lowest values are generally reached in winter, due to the fact that the infiltration sources are blocked at the surface (snow cover). The highest values recorded in spring exceeded the height of the piezometric pipe which extends 0.7 m above the ground, so that the real artesian groundwater pressures could not be determined exactly; however the maximum artesian pressure should not exceed 2 m.

Another surprising fact is the speed of variation of these groundwater fluctuations, in downward movement (7 m of descent in 32 days, for instance) as well as in upward movement (5.3 m of uplift in 2 days, in December 1998). These fluctuations are quite frequent, which proves the independence of groundwater conditions between the superficial aquifer within the sliding mass and the deep aquifer in the bedrock.

The discrete pressure measurements in the SINCO cell installed at the basis of TO1 borehole, at a depth of 12.5 m, are always some 2 m lower than the values measured in the micropiezometer TO1. As this discrepancy is constant it must be due to an unappropriate calibration of the cell in laboratory, but the numerous simultaneous measurements allow a correction of the directly measured values in order to obtain significant data. On the other hand, the calibration of the cell located in the micropiezometer TO1 could be checked during the spring when the water was overflowing.

The very low permeability of the sliding mass which could be assessed on the basis of the resistivity results (approximately 10^{-6} m/s) thus explains the minor variations of groundwater level near the surface, as recorded by the piezometer TO3, whereas the pressure in the bedrock fluctuates significantly. Both aquifers can thus be considered as independent, which will have to be taken into account in the various assumptions done in the slope stability computations.

In order to try to justify the sharp fluctuations of groundwater pressure in the bedrock, the continuously recorded groundwater levels in micropiezometer TO1 were compared with the daily rainfall data registered at La Valsainte ISM rain gauge station, which is located less than 3 km to the south of the slide, at the same altitude (1'455 m). Figure 5 displays such a comparison during 8 months including winter and spring seasons. Thus most of the sharp rises in groundwater level correspond to major rainfall periods, with a very short lag of 1 to 2 days, except when the precipitations fall under the form of snow, as in January and February. Furthermore daily rainfall of some 10 mm are sufficient to cause a marked rise in the piezometric level. As far as the drainage of the bedrock is concerned, it is slower and needs a period of one month without major rainfall to cause a marked descent of the groundwater level, for instance in November 1998.

According to the recorded climatic conditions during the

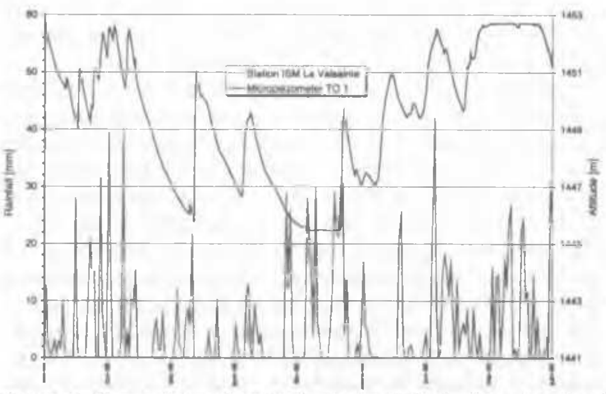

Figure 5. Comparison of groundwater level fluctuations in micropiezometer TO1 (upper curve) with rainfall data recorded at a nearby rain gauge station (lower curve) (the ground surface at the piezometer is located at El. 1'452 m)

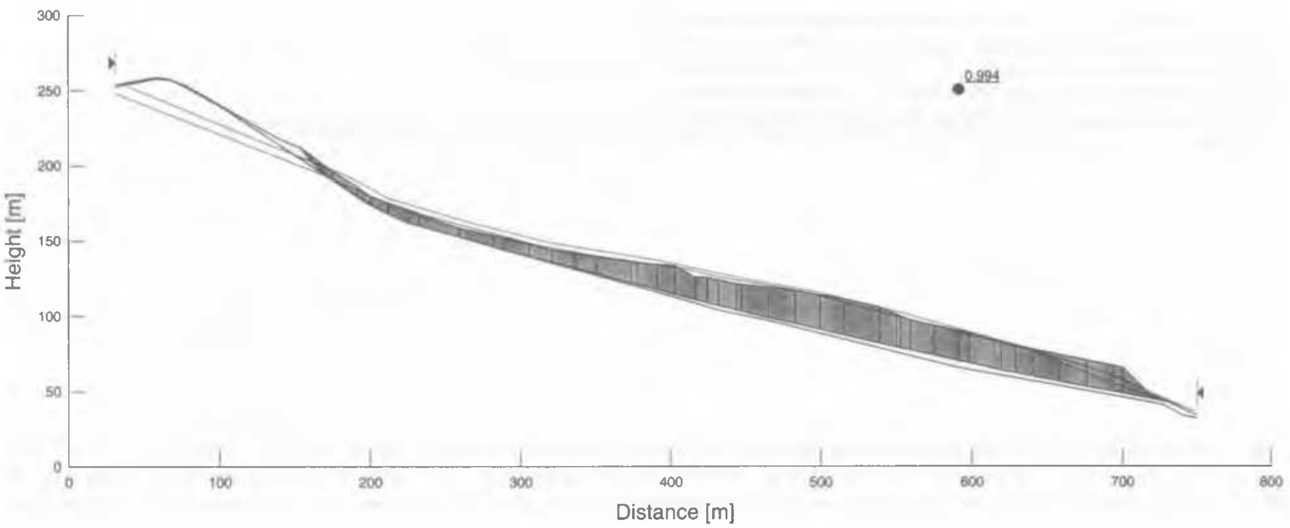

Figure 6. Cross-section of Creux d'Enfer slide passing by TO1 and TO2 boreholes, with result of slope stability computation (F_s = 0.99) when a groundwater level at the surface of the slide plus a groundwater pressure in the bedrock inducing an artesian head of 3 m are considered.

monitoring period, it is expected that the observed range of groundwater level in the bedrock, of some 8 m, is probably the maximum variation to be considered in slope stability computations to model extreme conditions.

The minimum recorded groundwater level of 6.6 m below the ground level is higher than the top of the bedrock, which means that the slip surface is always submitted to positive pressures, which may vary from 0 to 100 kN/m^2, in the vicinity of borehole TO1; this pressure is even higher in the area of the other borehole TO2, as it may be assessed between 130 and 180 kN/m^2. However, this higher pressure may have a smaller impact on the landslide mass itself, as a layer of morainic material of very low permeability separates the sliding mass from the bedrock.

Finally, if we consider the annual precipitation over a long term period, as recorded at la Valsainte ISM Station, one can state that the year 1998 has been one of the driest during the last 20 years. This particular condition, combined with the very sound state of the forest covering the whole landslide, may explain why no displacements have been recorded during the study period, whereas the morphology of the area clearly displays signs of instability.

5 ASSESSMENT OF SLOPE STABILITY CONDITIONS

In order to assess the actual stability conditions of the Creux d'Enfer landslide, several slope stability computations have been carried out, using SLOPE/W code with different analysis methods (Bishop, Janbu, Morgenstern & Price), the latter giving the most significant results.

With the fairly high value obtained for the friction angle by a H12 Geonor shear test, of Ø = 34°, the results are not surprising and give high factors of safety. Even if a more probable value of residual friction angle is selected, namely $\phi_r = 28°$, the factor of safety is 1.23 if only a groundwater level at the ground surface is considered.

It is thus necessary to model the equilibrium of the slope with two distinct groundwater conditions, namely the groundwater level in the landslide mass at the surface of the ground, plus a water pressure in the bedrock inducing an artesian head of some 3 m.

In this case, the result of which is shown in Figure 6, the obtained factor of safety is just below 1 (F_s = 0.99). Therefore it can be assumed that such pressures occurred in the very rainy years of 1994 and 1995, which must have induced a certain reactivation of the slide. However, the small size of the slide, as well as the particular geometry of the slip surface that was inferred from the geophysical results presented above, must induce a fairly quick stabilization as soon as the water pressures in the bedrock decrease, by seepage through the sandstone layers and also through the cracks that may develop up to the ground surface.

It is thus not quite surprising that this particular slide with a gentle slope, selected for its smaller size in relation to the need to assess the role of the forest on the stability conditions, did not display movements during the study period, which was fairly dry. It must also be stated that, as the slope is oriented to the north at an altitude of some 1'500 m, the snowmelt episode lasts during several months so that an extreme spring stability condition is not observed as on other slopes oriented to the south or the west.

6 CONCLUSIONS

Despite of the lack of actual movements at the Creux d'Enfer slide during the study period, the data gathered by geophysical methods to precise the shape and characteristics of the slip surface and by groundwater monitoring to determine the critical water pressures to be considered have lead to a better understanding of the stability conditions of this forested slope and have allowed an indirect explanation of the 1994 crisis of Chlöwena Landslide which was located nearby in a similar geological setting (Vulliet & Bonnard, 1996). Of course the particular piezometric variations recorded in the bedrock seem to prove that the stability of this gentle slope is practically not incluenced by the state of the forest and its evapotranspiration potential. However in a less contrasted hydrogeological context, the conclusions drawn here concerning the role of the forest might be different.

7 REFERENCES

Raetzo, H., Stiefelhagen, W., Pugin, A., Lateltin, O., Müller, I. 1995. Geophysikalische Messungen zur Beurteilung von Rutschungen, Fallbeispiel Falli Hölli (Kt. Freiburg, Schweiz). *Schweizer Ingenieur und Architekt 48* : 1109-1111.

Stiefelhagen, W. 1998. Radio Frequency Electromagnetics (RF-EM) : Kontinuierlich messendes Breitband-VLF, erweitert auf hydrogeologische Problemstellungen. *Doctoral Thesis, Centre of hydrogeology*, University of Neuchâtel, Switzerland.

Turberg, P. 1994. Apport de la cartographie radiomagnétotellurique à l'hydrogéologie des milieux fracturés. *Dotctoral Thesis, Centre of hydrogeology*, University of Neuchâtel, Switzerland.

Turberg, P., Müller, I., Flury, F. 1993. Hydrogeological investigation of porous environments by radio magnetotelluric-resistivity (RMT-R 12-240 KHz). *Journal of Applied Geophysics*, 31 *(1994)* : 133-143, Elsevier Sciences B.V., Amsterdam.

Vulliet, L. & Bonnard, Ch. 1996. The Chlöwena Landslide : Prediction with a Viscous Model. *Proc. VIIth Int. Symp. on Landslides*, Vol. 1 : 397-402.