Modelling creeping slopes

Laurent Vulliet*

Summary

Slowly moving landslides are common in many areas of the world. The analysis of their mechanical behaviour and kinematics is crucial for the evaluation of landslide risk. To carry out such an analysis proper numerical models are needed.

The paper describes a 3D viscous model and a 2D elastoviscoplastic model both developped by the Author and coworkers. The results of some applications regarding Swiss landslides are shortly described.

1. Introduction

Many areas in the world are known as being affected by slow landslide movements. In general the long-term velocity of these gently sloping slides varies between 1 and 10 cm/year, so that the movements do not create major problems to the buildings and roads on the surface, due to the thickness of the landslide masses. In some cases however a large reactivating process may occur, wherein velocities may be suddenly multiplied by 100 to 1000.

Limit equilibrium analysis as well as elastoplastic analysis cannot simulate the kinematics of these creeping and slowly sliding slopes.

Two approaches are reviewed here that can account for the viscous nature of soil masses. They have been developed by the author in collaboration with different researchers (see an extract of the bibliography in the references). The first approach is a three-dimensional model that is capable of describing the slow motion of natural slopes which may creep (deform within their body) and slide along their basal surface. Both single-phase and two-phase models were developed. The soil is modelled as a non-Newtonian viscous body with rate-dependent stress. Equations are solved using finite differences and various time integration algorithms.

The second approach deals with the 2D finite element analysis of an elastoviscoplastic body. The Perzyna's theory is used together with the HISS model of Desai and coworkers. Inteface elements can simulate the behaviour on the basal surface.

* Soil Mechanics Laboratory, Swiss Federal Institute of Technology, Lausanne, Switzerland

2. Non linear viscous models

2.1. Generalities

The detailed equations of the proposed non linear viscous models have been published elsewhere and will only be summarised here. The enclosed references by Vulliet and Hutter concern some aspects of the single-phase incompressible creeping mass model, the case of slopes with multi-layers and multi-sliding surfaces, and a continuum model for a two-phase mixture incorporating coupling effects. Rate-dependent constitutive laws are presented in detail by VULLIET & HUTTER [1988b] for the creeping solid mass and by VULLIET & HUTTER [1988c] for the sliding on the base.

The geometry of the problem is defined in Figure 1. The coordinate system is inclined with an angle α with respect to the horizontal. The free surface $z_s(x,y,t)$ moves with time but the base of the landslide (the sliding surface) $z_B(x,y)$ is considered fixed. In the case of the two-phase model, a second free surface is introduced, namely the phreatic surface $z_w(x,y,t)$ and hydraulic gradients may be imposed on the boundaries.

2.2. One-phase viscous model

In the case of one-phase body, governing equations are the balance laws of mass and momentum for an incompressible single phase solid (similar to a total stress analysis in soil mechanics).

The soil is assumed to be a non-Newtonian viscous body and its constitutive law takes the form

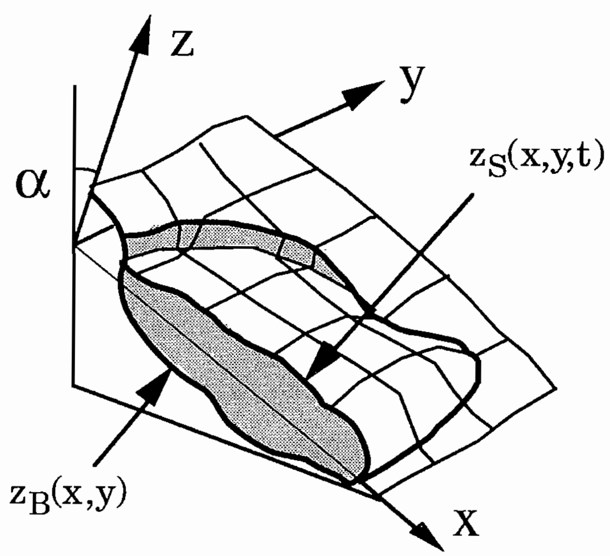

Fig. 1 – Coordinate system for the viscous model.
Fig. 1 – Sistema di riferimento per il modello viscoso.

$$D = f(t_{II})\,t \qquad (1)$$

where t_{II} is the second invariant of the deviatoric stress tensor **t**, **D** is the stretching tensor defined by

$$D_{ij} = \frac{1}{2}(v_{i,j} + v_{j,i}) \qquad (2)$$

with **v** the velocity vector.

Kinematic and dynamic boundary conditions must be stated for both boundaries z_S and z_B. The free surface $z=z_S(x,y,t)$ is assumed stress-free.

At the fixed base $z=z_B(x,y)$, the following dynamic condition applies:

$$v_B = -F_B(\tau_B)\,\vec{\tau}_B \qquad (3)$$

where $\mathbf{v}_B$ is the sliding velocity vector at the base, $\vec{\tau}_B$ the shear stress vector at the base, $F_B(\tau_B)$ a viscous-type sliding law function of the norm τ_B of the shear stress vector. Different expressions for F_B are proposed by VULLIET & HUTTER [1988c] for total and effective stress analysis and are validated for different landslides. Most of them were obtained from the Sallèdes data set. In the case of the Chlöwena landslide presented next, only two simple forms were used. The first one is the power law (Weertman's law)

$$F_B = B\,\tau_B^{\,n-1}, \qquad (4)$$

and the second one includes a threshold stress τ_o, more appropriate for stick slip:

$$\left.\begin{aligned} F_B &= 0 && \text{if}\ \tau_B \le \tau_0 \\ F_B &= B\frac{(\tau_B - \tau_0)^n}{\tau_B} && \text{if}\ \tau_B > \tau_0 \end{aligned}\right\} \qquad (5)$$

Although the governing equations are general for any three-dimensional gravity-driven sliding mass, it is of great mathematical and numerical advantage to consider the very special geometry of most landslides to perform a scaling followed by an asymptotic development, thus considerably simplifying the governing equations. This is known in hydraulics and glaciology as «shallowness assumption».

The numerical model takes full advantage of the analytical simplifications. Partial derivatives are expressed in terms of finite differences with an explicit time-stepping scheme [VULLIET, 1995].

2.3. Two-phase viscous model

In the case of the two-phase body, governing equations are the balance laws of mass and momentum for a compressible two-phase solid (similar to an effective stress analysis in soil mechanics with hydro-mechanical coupling). The soil is assumed again to be a non-Newtonian viscous body, but here the porosity (or as a first approximation the mean effective stress) enters in the constitutive law. Equations are more complex since field variables include not only the solid grains velocity but the water phase too [VULLIET & HUTTER, 1988a].

2.4. Chlöwena landslide

As an illustration of the viscous approach, the recent case study of Chlöwena landslide is presented. In July 1994, the large slowly sliding mass of soil was about to reach the bottom of the valley when we were asked to predict its final location and the size of the resulting dam [KRISENSTAB CHLOEWENA, 1994; BONNARD *et al.* 1995; LATELTIN & BONNARD, 1995; RAETZO, 1996]. It was a typical engineering situation: calculation had to be done quickly through the week-end with very limited information on the geotechnical characteristics of the landslide. We used the non-linear viscous landslide model for one-phase body [LMS, 1994; VULLIET, 1995; VULLIET & BONNARD, 1996]

This case was a real *a priori* calculation, months before the landslide reached its presently stable position, and was presented in a written report in August 1994 [LMS, 1994]. Figure 2 gives a schematic situation map of the Chlöwena landslide; the mesh geometry is given in figure 3 and material parameters in sliding laws (Eqs. 4 and 5) are listed in Tab. I. Calculated velocity fields are shown in figures 4 and 5 for two different sliding laws. Note that after 40-60 days, the sliding material is following the Höllbach river bed.

The flow field is strongly affected by the sliding law type: for the material 1 (power law) the velocity field is not contrasted and the entire movement soon occurs at a constant velocity. This does not correspond to the information we had.

For the material 2 (threshold stress) the velocity field is much more contrasted; after a while the movements tend to slow in the upper part of the

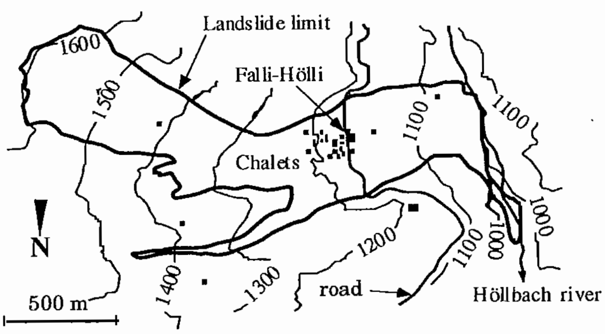

Fig. 2 – Schematic situation map of the Chlöwena landslide.
Fig. 2 – Mappa schematica della frana di Chlöwena.

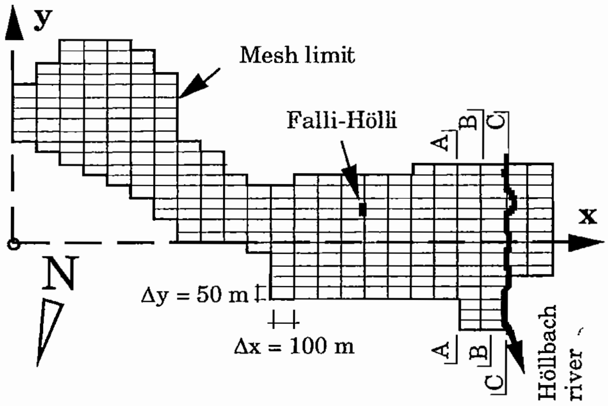

Fig. 3 – Mesh geometry (Chlöwena landslide).
Fig. 3 – Geometria della griglia (frana di Chlöwena).

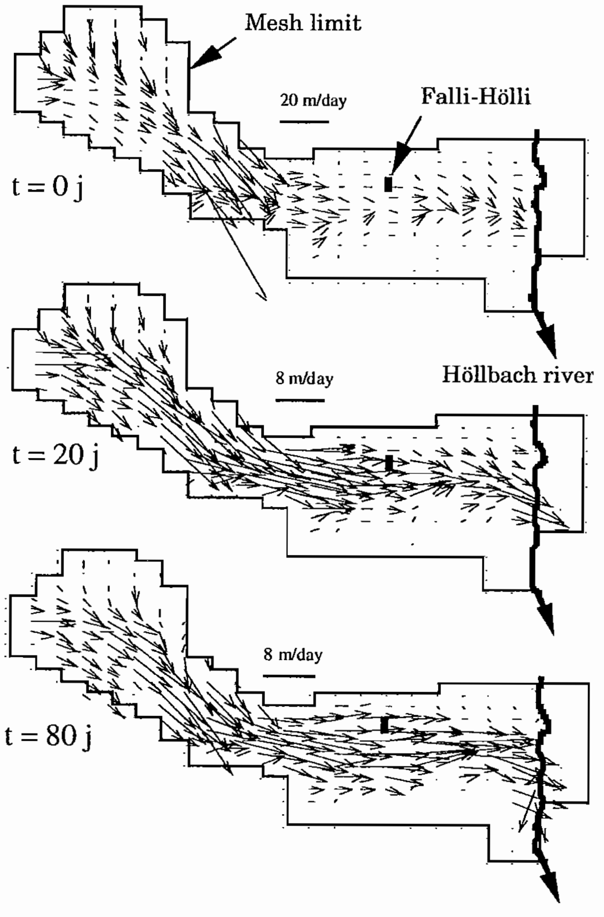

Fig. 4 – Calculated velocity field (material 1, power law).
Fig. 4 – Campo di velocità calcolato (materiale 1, legge potenza).

landslide, corresponding better to the measurements.

The period calculated was 200 days and although the mass was still moving slightly we could not see any major change in the dam geometry. We decided to stop there and consider the result of figure 6 as our first estimate of the geometry of the future dam. The total height was about 40 m.

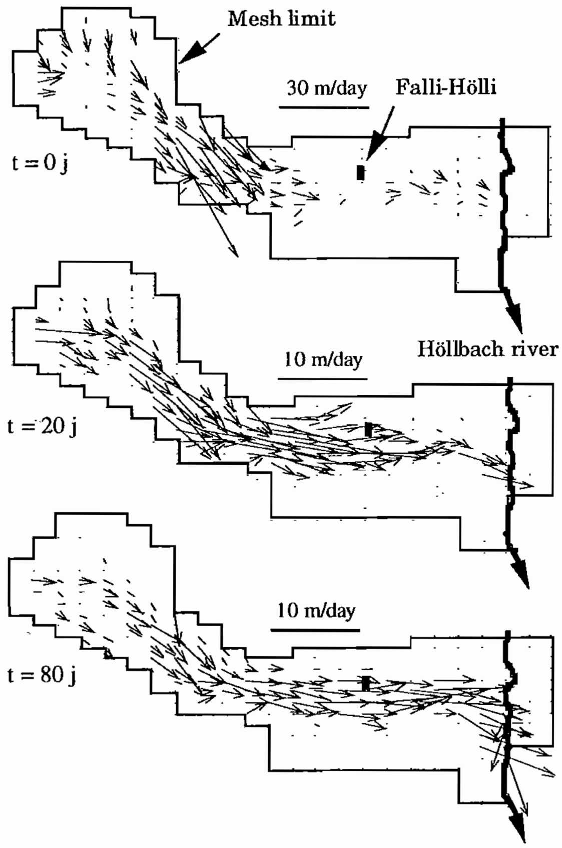

Fig. 5 – Calculated velocity field (material 2, with threshold stress).
Fig. 5 – Campo di velocità calcolato (materiale 2, con tensione di soglia).

This information was communicated to the crisis staff headquarters by August 15, 1994 [LMS, 1994].

On figure 6 the measured position of the dam is indicated by dashed lines and compared with the prediction. Considering the crude assumptions used the prediction is acceptable.

3. Elasto-viscoplastic model

3.1. Generalities

The second approach deals with elasto-viscoplasticity and key words are Perzyna's theory, HISS constitutive model, finite element method, interface elements and 2D analysis.

Tab. I – Material parameters in sliding laws.
Tab. I – Parametri del materiale nella legge di scorrimento.

Material no	*Eq. no*	*B*	τ_0 *[kPa]*	*n [-]*
1	(4)	$3.24°10^{-9}$ ms^{-1}kPa^{-2}	–	2
2	(5)	$1.74°10^{-6}$ ms^{-1}kPa^{-1}	80	1

A constitutive model is proposed for soils and interfaces involved in creeping natural slopes. It is based on the hierarchical single-surface plasticity and visco-plasticity approaches (HISS by Desai and coworkers) and allows for factors such as elastic, plastic and creep strains, normal stress and stress path effects. Details are presented in [VULLIET & DESAI, 1989; DESAI *et al.*, 1995; and SAMTANI *et al.*, 1996]. Some relevant equations are (for the solid):

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^{e}_{ij} + \dot{\varepsilon}^{vp}_{ij} \qquad (6)$$

$$\dot{\varepsilon}^{vp}_{ij} = \Gamma(\phi(F)) \frac{\partial Q}{\partial \sigma_{ij}} \qquad (7)$$

$$F = J_{2D} - (-\alpha J_1^2 + \gamma d_1^n)(1 - \beta S)^m \qquad (8)$$

$$Q = J_{2D} - (-\alpha J_1^2 + \gamma d_1^n)(1 - \beta S)^m \qquad (9)$$

where Eq. (6) gives the conventional decomposition of strain increment in elastic (e) and viscoplastic (vp) part and Eq. (7) gives the evolution of the viscoplastic strain increment. The function $\Gamma<\phi(F)>$ has the meaning of the inverse of a viscosity; laws are proposed in the mentioned references. F and Q are the yield function and plastic potential with stress invariant J_1 and J_{2D}, stress ratio S, hardening parameter α and α_Q, material constants γ, n, β and m. Figure 7 represents the yield function F in the J_1-J_{2D} plane and in the π plane. Similar developments were done for interface elements.

The model was calibrated from a series of laboratory triaxial tests for soils obtained from the field site of Villarbeney (Switzerland), simple shear tests for interfaces, and simple shear creep tests for both. Tests were performed both in Switzerland (at EPFL) and in the USA (at the University of Arizona). The model was implemented in a 2D finite-element procedure.

3.2. Villarbeney landslide

The model was used to back-predict observed field behaviour at two locations at the Villarbeney landslide [DESAI *et al.*, 1995; SAMTANI *et al.*, 1996]. A schematic situation map is given in figure 8 while figure 9 shows the finite-element mesh used for location E1. Comparison between measured and calculated velocity profile is presented in figure 10. It can be seen that the proposed modelling procedure provides highly satisfactory correlation for the field situation considered.

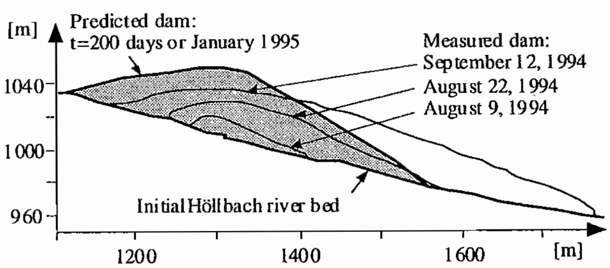

Fig. 6 – Evolution of the dam geometry created at the foot of the Chlöwena landslide.

Fig. 6 – Evoluzione della geometria della diga realizzata al piede della frana di Chlöwena.

4. Conclusions

Two very different types of viscous models for landslides are reviewed here. They both show potentials and they both have limitations.

The flow models (non linear viscosity) have the advantages of being 3D, simple to use (at least for the one-phase incompressible model) and the material parameters can be calibrated by means of field measurements. Drawbacks however are the lack of elastic strain and the limitations introduced by the shallowness assumption (no local effects can be taken into account like anchor or pile).

The elasto-viscoplastic model is strong on the constitutive level and gives a full 2D analysis incorporating local effects (time dependent stress developments on retaining walls for example); however, 3D effects are not incorporated (especially the lateral spreading plays an important role in real cas-

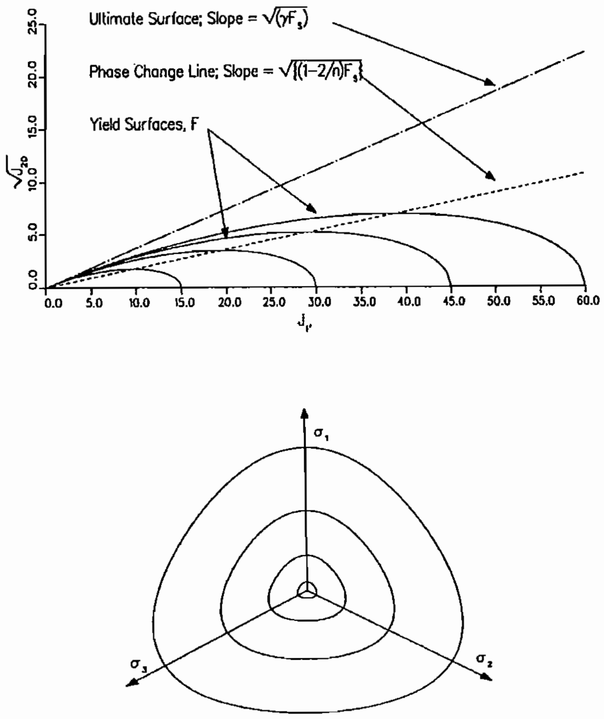

Fig. 7 – Yield function F in the J_1-$J_{2D}^{0.5}$ plane and in the π plane used in the elasto-viscoplastic model (Eq. 8).

Fig. 7 – Funzione di snervamento F nel piano J1 , J2D e nel piano p utilizzando il modello elasto - viscoplastico (Eq. 8).

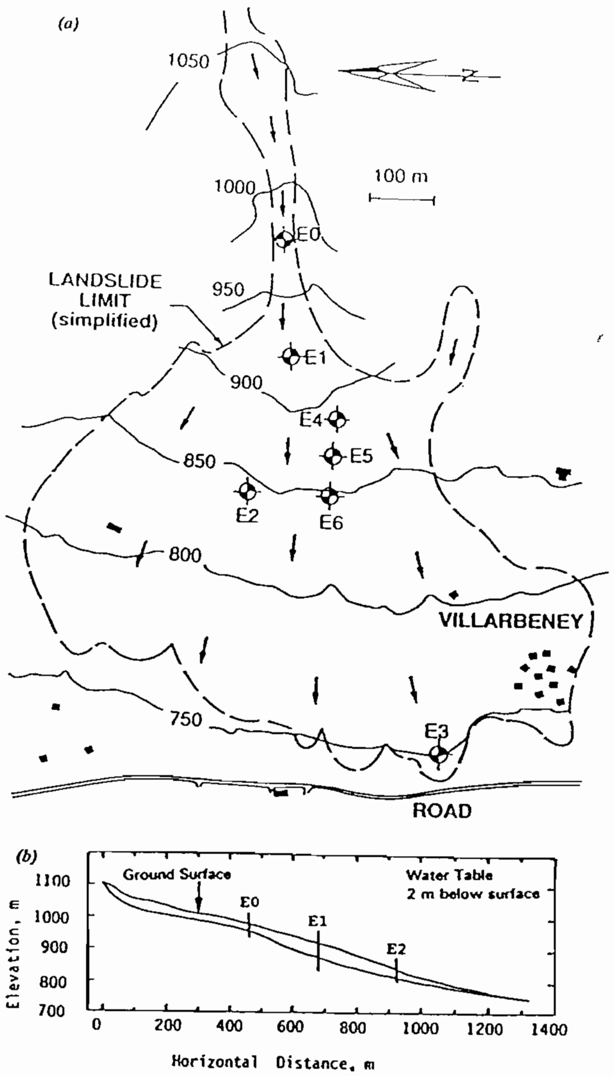

Fig. 8 – Schematic situation map of the Villarbeney Landslide.
Fig. 8 – Mappa schematica della frana di Villarbeney.

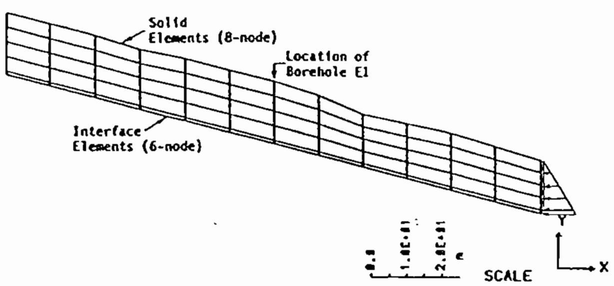

Fig. 9 – Finite-element mesh used for location E1 (Villarbeney Landslide).
Fig. 9 – Griglia agli elementi finiti utilizzata per il sito E1 (frana di Villarbeney).

es), full hydromechanical coupling is not done yet, and material parameters are more complex to find.

Another important limit is common to any modelling technique: the prediction will always depend

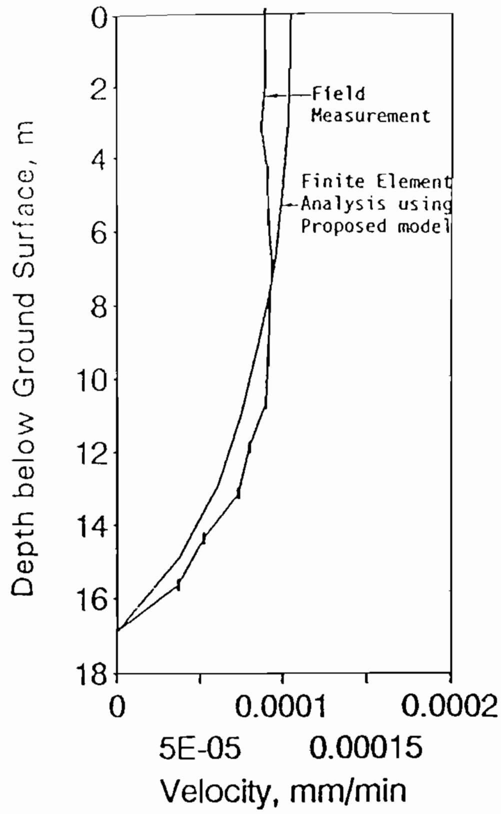

Fig. 10 – Comparison between measurements and calculated velocity profile at location E1 (Villarbeney landslide).
Fig. 10 – Confronto fra il profilo di velocità calcolato e misurato al sito E1 (frana di Villarbeney).

on the quality of the predicted boundary conditions (in particular the groundwater heads). We are presently working on cognitive methods to improve this aspect (see in this issue the article by Mayoraz and al. on neural networks).

Although much work is still needed in the domain of the prediction of slow movements of slopes, the proposed model can surely serve as a base for further developments.

Acknowledgements

This paper is dedicated to the memory of Danilo Zuffi, member of the Krisenstab Chlöwena. The author would like to thank Mr Lunven for his help in performing some of the computations for the Chlöwena landslide as well as Mr Ch. Bonnard for his helpful discussions and the Krisenstab Chlöwena Messrs. Zosso, Briel, Philipona, Raetzo and Gétaz. Part of the presented results were obtained during the stay of the author at the University of Arizona jointly with his PhD student N. Samtani and Regents' Prof. C.S. Desai. The viscous model was developed thanks to a still active collaboration with Prof. K. Hutter.

References

BONNARD CH., NOVERRAZ F., LATELTIN O., & RAETZO H. (1995) – *Large landslides and possibilities of sudden reactivation*. 44th Geomechanics Colloquy, Salzburg (to be published)

DESAI C.S., SAMTANI N. & VULLIET L., (1995) – *Constitutive modelling and analysis of creeping slopes*. J. of Geotechnical Engineering, *ASCE*, vol. CXXI, n. 1, January, pp. 43-56

KRIESENSTAB CHLOEWENA (1994) – *Grossrutschung Chlöwena, 1*. Technischer Bericht, Tafers im August.

LATELTIN O. & BONNARD CH. (1995) – *Reactivation of the Falli-Hölli landslide in the Prealps of Freiburg, Switzerland*. Landslide News, n. 9.

LMS (1994) – *Glissement de Chlöwena, Etude prévisionnelle sur le comportement du glissement*. Rapport du Laboratoire de mécanique des sols de l'EPFL, S5719, Août.

RAETZO H. (1996) – *Rutschung Falli-Hölli, ein ausserordentliches Ereignis?* Int. Conf. INTERPRAEVENT, Graz (to be published).

SAMTANI N., DESAI C.S. & VULLIET L. (1996) – *An interface model to describe viscoplastic behaviour*. Int. J. for Num. and Analyt. Meth. in Geomechanics, vol. XX, pp. 231-252.

VULLIET L. & HUTTER K. (1988a) – *Continuum model for natural slopes in slow movement*. Géotechnique vol. XXXVIII, n. 2, pp. 199-217.

VULLIET L. & HUTTER K., (1988b) – *Set of constitutive model for soils under slow movement*. J. of Geot. Eng. Div., *ASCE*, vol. CXIV, n. 9, pp. 1022-1041.

VULLIET L. & HUTTER K. (1988c) – *Viscous-type sliding laws for landslides*. Can. Geotech. J., 25, pp. 467-477.

VULLIET L. & DESAI C.S. (1989) – *Viscoplasticity and finite elements for landslide analysis*. Proc. 11th Int. Conf. on Soil Mech. and Found. Engrg, Rio de Janeiro, Brazil.

VULLIET L. (1995) – *Predicting large displacement of landslides*. Proc. 5th Int. Symp. on Numer. Meth. in Geomechanics, NUMOG V, Davos, Switzerland, 6-8 September, pp. 527-532.

VULLIET L. & BONNARD CH. (1996) – *The Chlöwena landslide: Prediction with a viscous model*. Proc. XII Int. Symp. on Landslides, Trondheim, June.

Modellazione di pendii soggetti a creep

Sommario

In molte aree sono attivi movimenti franosi lenti. L'analisi del loro comportamento meccanico e della cinematica dei movimenti è spesso fondamentale per la valutazione del rischio di frana. Per questo sono necessari appropriati modelli meccanici. L'articolo descrive due modelli, uno viscoso (3D) e l'altro elasto-viscoplastico (2D), sviluppati dall'Autore in collaborazione con altri ricercatori. Vengono inoltre riportati i risultati di alcune applicazioni relative a frane in atto nelle Alpi svizzere.

PRECISAZIONE

Riportiamo di seguito l'indicazione delle affiliazioni accademiche dei Professori Adolfo Foriero e Branko Landanyi, autori dell'articolo *Finite elements analysis for large strain consolidation of satured clays under equilibrium conditions*, apparso sul n. 2/98 della «Rivista Italiana di Geotecnica»

– Adolfo Foriero, Départment de génie civil, Université Laval, Sainte-Foy (Québec) Canada.
– Branko Landanyi, École Polytechnique, Montréal (Québec) Canada.