Geogr. Fis. Dinam. Quat.
34 (2011), 45-53, 11 figg., 1 tab.

DOI 10.4461/GFDQ.2011.34.5

THEODORE.W.J. VAN ASCH (*) (**) & JEAN PHILIPPE MALET (***)

ANALYSING THE KINEMATIC RESPONSE TO GROUNDWATER FLUCTUATIONS OF A SLOW MOVING LANDSLIDE IN VARVED CLAYS, USING TWO ALTERNATIVES OF THE EQUATION OF MOTION

ABSTRACT: VAN ASCH TH.W.J. & MALET J-P., *Analysing the kinematic response to groundwater fluctuations of a slow moving landslide in varved clays, using two alternatives of the equation of motion*. (IT ISSN 0391-9838, 2011).

The relation between groundwater fluctuations and displacement velocities are analysed for a slow moving deep-seated landslide. The landslide, which developed in varved clays, is situated near Monestier-du-Percy, on the «Trièves Plateau» in the French pre-Alps. The landslide, which started in the fifties, moved over a long time period with varying (also zero) velocities. Over longer periods, a temporally attenuating trend in the amount of displacement could be observed. In recent years during the nineties, inclinometer measurements showed a mean displacement around 30 mm yr^{-1}. The inclinometer profiles show a shear band of less than one meter with a more or less rigid plug on top.

Two models based on the equation of motion were tested on these displacement profiles in combination with piezometric observations from an open stand pipe nearby: The AC-model uses the complete equation of motion including the local and convective acceleration terms. The NA-model ignores these terms making it a sort of steady state model. It appeared that for slow moving landslides, differences in calculated velocities and displacements between the two models can be neglected for gradual rising and falling groundwater levels.

The landslide monitoring did not show a simple linear relation between groundwater level fluctuation and displacement velocity. Back calculation of the viscosity for the various time intervals within a selected test period between 23/11/1992-24/08/1995 shows an exponential relation ship between excess shear stress and shear strain rate. It can be explained by a rate dependency of an apparent viscosity, caused by generation of a rate dependent excess pore pressure or by a rate dependent change in thickness of the shear band.

KEY WORDS: Slow moving landslides, Equation of motion, Rate dependent viscosity, Excess pore pressure.

INTRODUCTION

Slow moving landslides show a wide variety of complex systems and mechanisms controlling their temporal displacement pattern. The movement of these landslides are in the first place controlled by a fluctuating groundwater level generating changes in pore pressure and thus changes in excess shear stress controlling the velocity. The rate in rise and fall of the groundwater level is influenced by the amount of fissures which provide the infiltrating water direct access to the groundwater body. During movement fissures may develop and may be closed again leading to a changing preferential flow regime (Corominas & *alii*, 1999; Malet & *alii*, 2005). Consequently, large landslides have shown an erratic and complex response to rainfall (Noverraz & *alii*, 1998; Malet & *alii*, 2005).

The displacement velocities within a landslide differ, which results in the generation of zones of compression and extension. This will create undrained loading effects, leading to the generation of excess pore pressure, (Baum and Fleming, 1991; Picarelli & *alii*, 1995, Giusti & *alii*, 1996, Klubertanz & *alii*, 2000, Comegna and Picarelli, 2005; van Asch & *alii*, 2006, 2009). Under compression, excess pore water pressures, as a result of undrained loading may generate sudden surges (Bonnard & *alii*, 1995, Baum and Fleming, 1991, Caron & *alii*, 1996).

Excess pore pressure effects can also be induced by sliding of the landslide body over an undulating slip surface, with destabilising positive and stabilising negative pore pressure developement as the result of compression and dilation at respectively the proximal and distal sides of bumps (Keefer & Johnson, 1983). Van Genuchten & van Asch (1988) found similar feedback mechanisms in intermittently sliding blocks of a slow moving landslide near La Mure (French Alps), which developed in varved clays.

(*) *Department of Physical Geography, University of Utrecht, Utrecht, The Netherlands.*

(**) *Delft University. of Technology, Water Resources Section, Faculty of Civil Engineering and Geosciences, Delft, The Netherlands.*

(***) *Institut de Physique du Globe de Strasbourg, School and Observatory of Earth Sciences (EOST), Strasbourg University, Strasbourg, France.*

This text is derived from a lecture given at the 3rd Meeting of the Italian Association of Physical Geography and Geomorphology, held in Modena on September 13, 2009 in honour of Prof. Mario Panizza.

Iverson (2005) and Goren & Aharonov (2009) pointed to the effect of compression and dilation in the shear zone and the balance between the generation of excess pore pressure and pore pressure dissipation, which may control the movement of landslides.

There are also consolidation effects, which during periods of rest, may lead to strength regain in the shear zone, attenuating the likelihood of reactivation (Nieuwenhuis 1991, Angeli & *alii*, 2004).

Van Asch & *alii* (2009) did an attempt to analyse groundwater level fluctuation in relation to the displacement of slow moving deep seated landslides, which developed in varved clays on the «Trièves Plateau» in the French pre-Alps. The aim of this paper is to analyse further this relationship, using two displacement models, which are based on two alternatives of the equation of motion.

First, a description of the landslide is given. Second, the field observations (displacement and groundwater) are presented. Third, the kinematical displacement models are presented based on two alternatives of the equation of motion. Finally, the paper analyses the differences between the two models and the influence of viscosity and excess pore pressure on the moving pattern of this landslide.

DESCRIPTION OF THE VARVED CLAYS LANDSLIDE MONESTIER-DU-PERCY

In the French Alps in the so called «Trièves» region, 50 km south of Grenoble, glacio-lacustrine clay sediments were deposited in glacially dammed lakes during the Würm maximum episode. They are characterised by an alternation of silt and clay laminae with a thickness of 1-20 mm (Giraud & *alii*, 1991; van Asch & *alii*, 1996). In these clay deposits many landslides have developed. The activity of most of these landslides is seasonal (Van Genuchten, 1989; van Asch & *alii*, 1996): movements are triggered by snowmelt and rainfall especially in spring time. These clayey landslides have slip surfaces which may be shallow (4 to 8 m) or more deep-seated (20 to 40 m) (Antoine & *alii*, 1981). Slope stability calculations indicate that the groundwater levels of these deeper slides have to rise nearby the surface in order to trigger or accelerate the movements (Vuillermet, 1992).

The geomorphological analysis of old aerial photographs (1948, 1956) of the Monestier-du-Percy landslide indicated instability signs of the slope since 1956. The landslide affects an area of approximately 0.9 km^2, with a relatively low-gradient slope (12°), and the land cover is mainly composed of pasture lands (fig. 1). The geology of

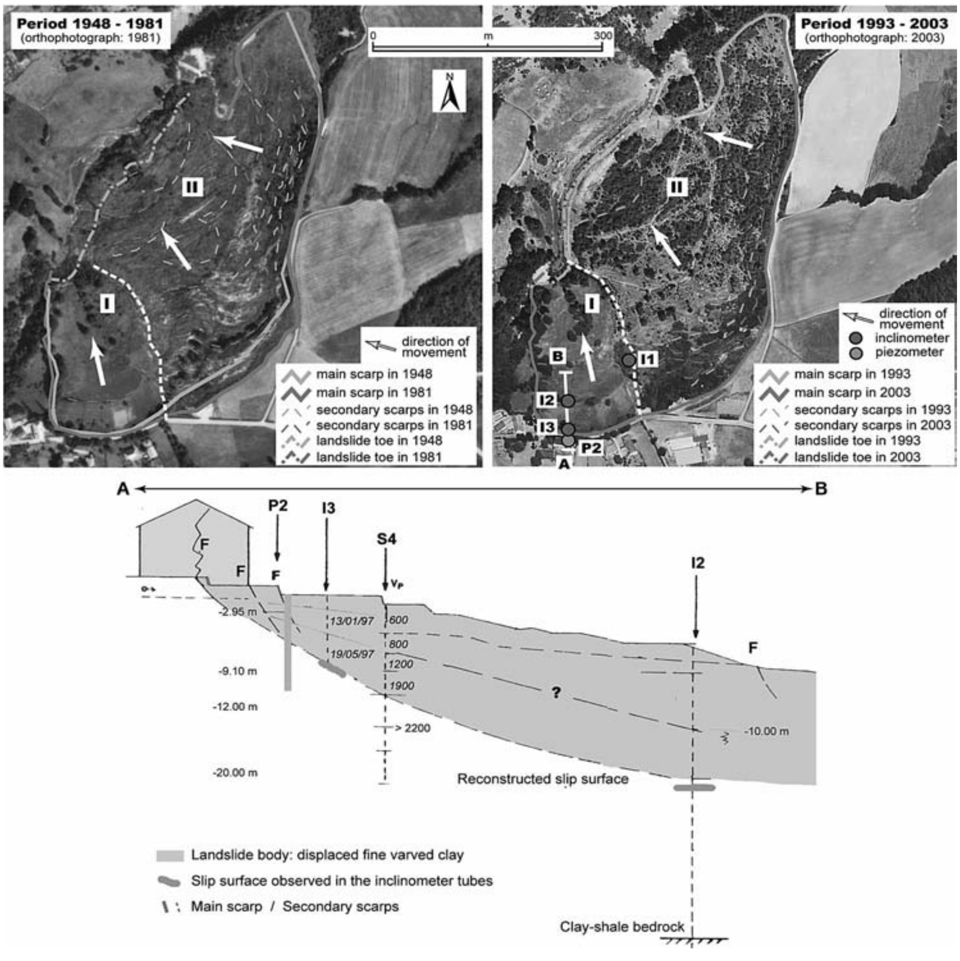

FIG. 1 - The Monestier-du Percy landslide: the displacement history, and instrumentation.

the site is composed of ca. 40 m of varved clays, which overlay a bedrock of Callovo-Oxfordian clay shales with a dip of ca. 40° in the South-West direction, whilst the landslide is developing in the North-West direction (Antoine & *alii*, 1981). The landslide mass can be divided into two parts (fig. 1), bordered by a positive undulation of the clay-shale bedrock:

- the South Western part is a landslide characterized by ca. 24 m of varved clays and a slip surface located at –16 m below the main houses and at –9 m nearby the road. The groundwater levels can attain the topographic level. This part of the slide affected 3 houses and the main road.
- the North-Eastern part, of the landslide is moving faster, with an erosion of the main scarp of 10 m between 1978 and 1988. The bedrock is located at –40 m, and the slip surface at a depth of –20 to –25 m.

Displacements could be calculated from analyses of ortho-rectified aerial photographs (fig. 1). In the period 1948-1981 mean velocities of 3.5 mm.yr^{-1} are observed with a progression of the toe of 1150 mm in the South Western part of the landslide. In the period 1993-2003, mean velocities of 50 mm.yr^{-1} are observed with a progression of the toe of 510 mm. In the North Eastern part the ortho-photographs show probably an attenuating trend in the displacement of the toe of about 30 m (1 m yr^{-1}) in the period 1948-1981 and for the 1993-2003 period 3 m (is 0.3 m yr^{-1}) (Van Asch & *alii*, 2009).

One piezometer (P1*)*, three inclinometers (I1, I2, I3) have been installed in order to better understand the mechanics and monitor the displacements and the hill slope hydrology (fig. 1).

Geomorphological observations and analysis of the geotechnical drillings indicate a rotational movement in the upper part of the landslide, and a translational movement in the lower part imposed by a flattening of the slip surface in the down slope direction.

ANALYSIS OF THE MORE RECENTLY OBSERVED INCLINOMETER DISPLACEMENTS

Fig. 2 shows the displacement profiles of inclinometer I_2 at the Monestier-du-Percy landslide over the period 23.11.1992-24.08.1995. The interval between two measurements ranges between one to two month(s) in the first stage of the measuring campaign. When a sufficient impression of the rate of displacement was obtained the period between two measurements was extended to 3 to 6 months.

At the Monestier-du-Percy landslide, the maximum deformation near inclinometer I_2 was found at a depth of around 15.5 m (fig. 2). The total displacement over nearly 3 years of measurements was about 80 mm, with an average of about 30 mm.yr^{-1}. The test period for which we could analyse the displacements in relation to groundwater fluctuations dated from 26-2-1993 until 20-6-1995, which is plus minus 28 months with a total displacement of nearly 63 mm. The displacement profiles (fig. 2) show a deformation zone of no more than 1 m with a more or less rigid plug with practical no internal shear deformation on top. The thickness of this shear zone may be less than 1 m but this could not be detected due to stiffness of the flexible tube. Van Genuchten (1989) observed a shear band with a thickness of 1.5 cm at a depth of 4.5 m in a varved clays landslide near La Mure.

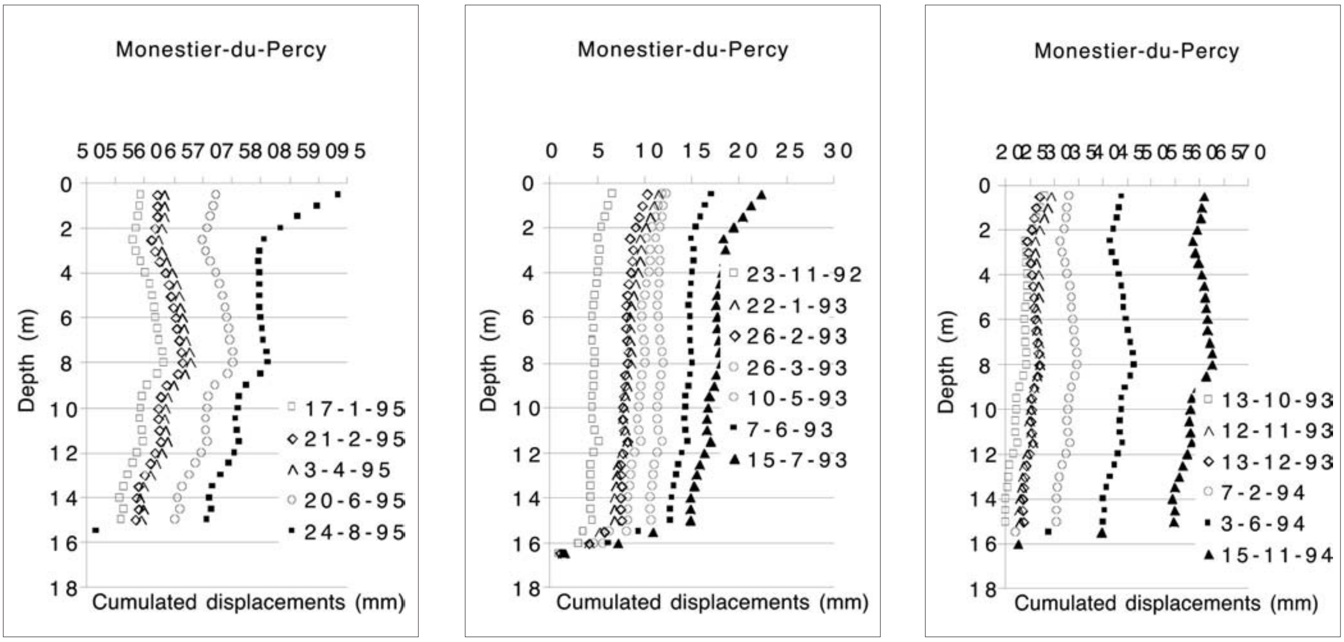

FIG. 2 - The displacement profiles of inclinometer I_2 at the Monestier-du-Percy landslide over the period 23.11.1992-24.08.1995.

HYDROLOGICAL OBSERVATIONS

Only one groundwater observation station is available, in the upper half of the landslide (fig. 1). The instrument is a standard open standpipe of 0.125 m in diameter. The piezometer P2 in fig. 1 was installed in a 10 m deep borehole with a filter between –5 and –10 m below the surface, fully in the varved clays deposits. Groundwater fluctuations are relatively small and range between 1 and 2 m. (fig. 3).

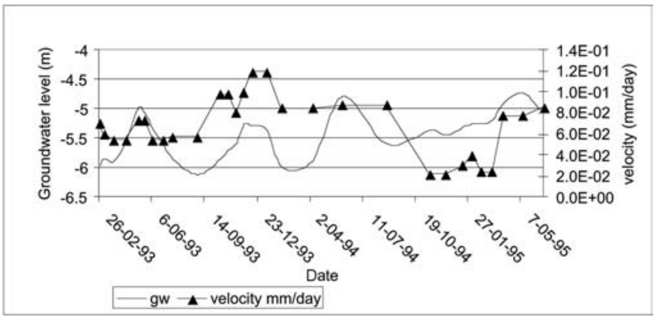

FIG. 3 - The groundwater fluctuations at the Monestier-du Percy landslide obtained from Piezometer P2 in relation to the mean observed velocities calculated from the periodical displacements of Inclinometer I2.

The fluctuation of the groundwater levels (measured per day) in fig. 3 are shown in combination with mean velocities calculated from the displacement for different observation intervals between January 1993 and July 1995, which were obtained from displacement measurements with inclinometer I_2. The figure shows a meagre correlation between the two time series. The maximum groundwater levels are observed in April-May and November-December. The fluctuation of the groundwater level in the varved clays may be regulated by a complex double reservoir hydrological system as was suggested by Van Asch & *alii*, 1996.

DESCRIPTION OF THE DISPLACEMENT MODELS

The models which are described here are two versions of the equation of motion where the forces are solved on a consideration of forces under dynamic condition of a moving body. The mass balance is given by Eq. (1):

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} = 0 \qquad (1)$$

where h is the vertical height (L), u is the velocity (LT^{-1}) t- time (T) and x distance (L) measured horizontally (see fig. 4).

The momentum balance in terms of acceleration, which can be used for both rapid and slow moving mass movements (Begueria & *alii*, 2009), is given by Eq (2):

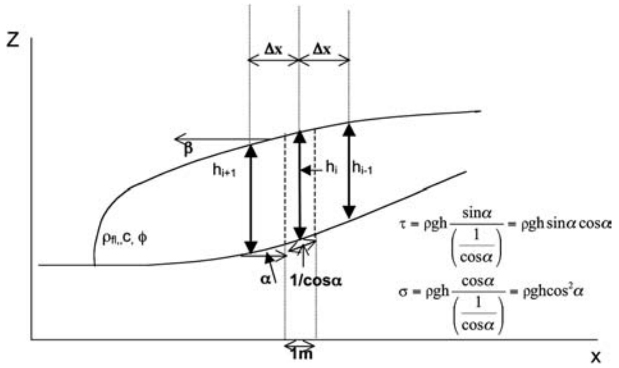

FIG. 4 - Scheme of the different slices with a unit width of 1 m and the shear stress and normal stress for each slice, which is used in the equation of motion. The nodal distance between the slices (Dx) is set at 20 m.

$$\frac{\partial u}{\partial t} + c_x u \frac{\partial u}{\partial x} = g c_x \left[\sin\alpha_x \cos\alpha_x - k \frac{\partial h}{\partial x} - S_f \right] \qquad (2)$$

where ρ (M) is mass and k is an earth pressure coefficient (-)i.e. the ratio between the tangential and normal stresses . $c_x = \cos\alpha_x$ is the direction cosine of the bed. The first and second term on the left side are respectively the local or time acceleration, expressing the time rate of change at a fixed position and the convective acceleration i.e. the time rate of change due to change in position in the spatial field. The first term on the right site is an acceleration term related to the gravity component (LT^{-2}). When one multiplies this term with rh it turns into a shear stress term which is depicted in fig. 4. The second term is a pressure term related to differences in lateral stress within the landslide during movement. S_f is a resistance term (-), which accounts for momentum dissipation within the landslide. If this is caused by frictional and viscous resistance it can be defined as Eq. (3):

$$S_f = \left[\cos^2\alpha_x \tan\varphi' + \frac{1}{\rho gh} \left(\tau_c + \eta \left(\frac{\partial u}{\partial z} \right)^b \right) \right] \qquad (3)$$

The first term multiplied by rgh turns into a Coulomb friction stress which is derived in fig. 4. The ϕ' in Eq. (3) is an apparent friction angle, which incorporates the effect of pore pressure. It can be described as follows Eq. (4):

$$\tan\varphi' = (1 - r_u)\tan\varphi \qquad (4)$$

Where r_u is the pore pressure ratio (-) defined as the ratio between the pore pressure p and the total stress rgh (ML^2T^{-2}/ ML^2T^{-2}) and ϕ (-) is the intrinsic friction angle of the material. The yield strength τ_c ($M L^{-1} T^{-2}$) is related to the cohesion of the material, $\partial u/\partial z$ (T^{-1}) is the shear strain rate and η is the dynamic viscosity ($M L^{-1} T^{-1}$). Normally the viscosity component is considered as a Bingham fluid where a linear stress-strain rate relationship is assumed when the frictional (ϕ) and (or) cohesive (τ_c) resistance is exceeded. For a Bingham fluid the exponent b in Eq. (3)

equals 1. However, in debris flows a convex relationship defining a shear thinning behavior (i.e. decreasing viscosity with applied shear) is in better agreement with most experiments, and led to definition of the Herschel-Bulkley model where b<1 in Eq. (3). An exponential relationship was also assumed for slow moving landslides: (Cartier and Pouget 1988, Salt 1988, Vulliet and Hutter (1988), Bracegirdle & *alii*, 1991, Conforth and Vessely 1991.

In analysing the kinematics of this slow moving landslide the momentum equation given in equation Eq. (2) will be called from now on the AC-model. This model can be simplified by ignoring the local and convective acceleration terms at the left side of Eq. (2) making it a steady state model, which we will call the NA-model Eq. (5):

$$g\sin\alpha_x\cos\alpha_x + kg\frac{\partial h}{\partial x} - g\left[\cos^2\alpha_x\tan\varphi' + \frac{1}{\rho g h}\left(\tau_c + \eta\left(\frac{\partial u}{\partial z}\right)^b\right)\right] = 0 \quad (5)$$

The AC-model can be solved numerically with b=1 (Bigham viscosity) in a simple form Eq. (6):

$$u_i^{n+1} = u_i^n - c_i^n\frac{\Delta t}{\Delta x}u_i^n\left(u_{i+1}^n - u_{i-1}^n\right) + \Delta t g c_i^n\left[\cos\alpha_i\sin\alpha_i - k\tan\beta_i^n - Sf_i^n\right] \quad (6)$$

where Sf Eq. (7):

$$Sf_i^n = \cos^2\alpha_i\tan\varphi' + \frac{1}{\rho g h_i^n}\left(\tau_c + \eta\frac{u_i^n}{d}\right) \quad (7)$$

where n is the time step and i the slice number (see fig. 5). In Eq. 7 we assume a linear increase of velocity over the thickness of a shear band with a constant thickness (d). When r is the thickness of the rigid plug on top we can numerically calculate the new height in slice i for the next time step n+1 using the mass balance given in equation (1) as follows Eq. (8):

$$h_i^{n+1} = h_i^n - \frac{\Delta t}{\Delta x}\{\tfrac{1}{2}\left[du_i^n - du_{i-1}^n\right] + \left[\left(ru_i^n\right) - \left(ru_{i-1}^n\right)\right] \quad (8)$$

The numerical scheme for the NA-model assuming b=1 in Eq. (3) can have the following form by replacing $\partial u/\partial z$ by u_i^n/d, which is a discrete velocity in slice i at time step n over a discrete thickness (d) of the shear zone Eq. (9):

$$g\sin\alpha_i^n\cos\alpha_i^n - kg\tan\beta_i^n - g\cos^2\alpha_i^n\tan\varphi'^n_i - \frac{1}{\rho h_i^n}\tau_c - \frac{\eta}{\rho h_i^n d_i^n}u_i^n = 0 \quad (9)$$

Solving u in Eq. (9) delivers the following form Eq. 10a-e)

$$u_i^n = \frac{\rho h_i^n d_i^n}{\eta}\left(D_i^n + P_i^n - S_i^n - C_i^n\right) \quad (10a)$$

$$D_i^n = g\sin\alpha_i^n\cos\alpha_i^n \quad (10b)$$

$$P_i^n = kg\tan\beta_i^n \quad (10c)$$

$$S_i^n = g\cos^2\alpha_i^n\tan\varphi' \quad (10d)$$

$$C_i^n = \frac{1}{\rho h_i^n}\tau_c \quad (10e)$$

A COMPARISON BETWEEN THE AC- AND NA-MODEL

The kinematics of the displacement was analysed over the period 8-2-1993 and 20-6-1995 which is a period of 879 days. The daily piezometric levels delivered a mean groundwater level of 10.24 m over that period. The total displacement in that time was 62.89 mm. These two figures have been used to back calculate the viscosity with the two models. The other parameters have been taken from the literature. Giraud & *alii* (1991) reported shear test results of four samples taken at depths between 4-10 m. at three locations in the Trièves basin. The shear tests results on varved clays sheared, along the laminae, showed peak friction values between 20° and 21° and residual values between 18° and 19°. Van Genuchten and van Asch, (1988) found back calculated friction angles values between 17°-19° for the La Mure landslide with a slip surface at a depth of 4.5 m. A large part of slip surface of the here presented landslide is nearly parallel to lamination of the clays and due to the frequent movements the friction angle is in a residual state. The highest residual friction values (19°) are selected as input for the models, since the slip surface in Monestier-du-Percy lies deeper than where the shear test samples were taken. (See table 1). The cohesion for the residual state is set to zero (Giraud & *alii*, 1991; See table 1) The earth pressure coefficient k (see Eq. (2)) was set at 0,75 and kept constant, assuming a static condition for this very slow moving landslide and a rigid moving body.

TABLE 1 - Parametric input values for the AC- and NA-model obtained from literature and from back calculation (in italic)

	Δx (m)	Time step	Φ (-)	c kPa	k	*η kPa s*
AC-model	20	1 day	19°	0	0,75	*2,12E+09*
NA-model	20	1 day	19°	0	0,75	*5,5E+08*

Fig. 5 show the profile along AB until the toe (see fig. 1), where the analyses were carried out. The distance between

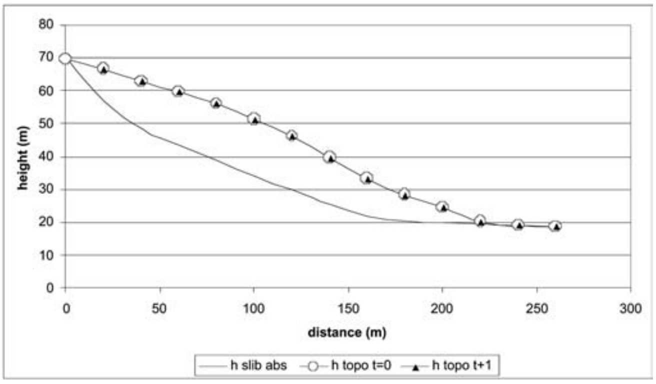

FIG. 5 - Cros section along the Monestier-du Percy landslide in the SW part along A-B until the toe (see fig. 1).

the centre of the slices (Δx) is set at 20 m and the time step at 1 day (see fig. 2 and table 1) Using the parameter values given in table 1, the back calculated viscosity over the period of 879 days with the mean groundwater table at –5.76 m and a measured horizontal displacement in that period of 62.89 mm brought for the AC-model a viscosity of 2.12E+09 kPa s and for the NA-model a viscosity of 5.5E+08 kPa s. Van Genuchten 1989 measured in the laboratory a viscosity of 2.53 E+08,with stress controlled direct shear tests.

The back analyzed viscosities and the parametric values given in table 1 were used to simulate for the test period the effect of the groundwater fluctuation on the cumulative displacement and the velocity.

The difference between the two models is first demonstrated by making a hypothetical simulation over 100 days using 3 different groundwater levels and the viscosity calibrated over 2.4 years displacement. fig 6 shows for the AC-model an acceleration and decelerations with respectively rising and falling groundwater before it comes to a steady velocity while the NA-model has an immediate response to the rise or fall in groundwater. Fig. 6 shows that the velocities of both models are nearly equal in the steady state period.

Fig. 7 shows a real world case. The calculated cumulative displacement with both models (AC and NA) in relation to the measured cumulative displacement and groundwater fluctuation are depicted for the test period. The figure shows no differences in cumulative displacement between the two models. In fact the differences in the cumulative displacement between the NA- and AC-model calculated at different times ranges between 0.17 and –0.38 mm during the 2.4 year test period. Also the effect of the groundwater fluctuations on the fluctuations of the cumulative displacement in that period is not visible. The cumulative displacements seem to be linear related mainly to the cumulative time. The cumulative displacement calculated with both models show clear deviations with the observed cumulative displacement in fig. 7. This indicates a more sensitive reaction of measured displacements in relation to groundwater fluctuations. This will be analyzed later on in more detail.

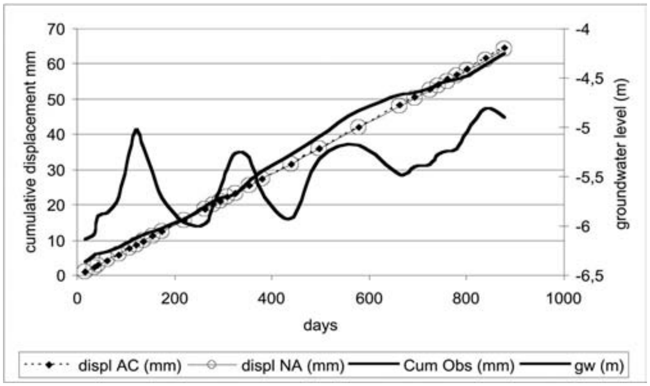

FIG. 6 - Cumulative displacements (observed and calculated) in relation to measured groundwater fluctuations of the Monestier-du-Percy landslide in the period 23.11.1992-24.08.1995.

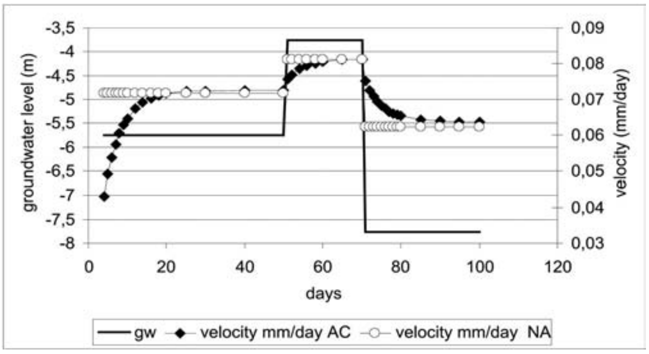

FIG. 7 - Hypothetical instantaneous groundwater fluctuations in relation to calculated velocities of the Monestier-du-Percy landslide for respectively the AC- and NA-model.

Based on the simulated cumulative displacements the mean velocity is calculated for each measuring interval. Fig. 8 shows velocities calculated with the AC- and NA-model in relation to observed groundwater rising and falling limbs. As can be expected from the model, the calculated velocity follows the trends of the groundwater fluctuations. One can see minor differences in fluctuations between the AC- and NA-model. During the minima of the groundwater level the AC-model velocities show slightly higher values than the velocities calculated with the NA-model. During the maximum rise of the groundwater these differences are negligible most of the time.

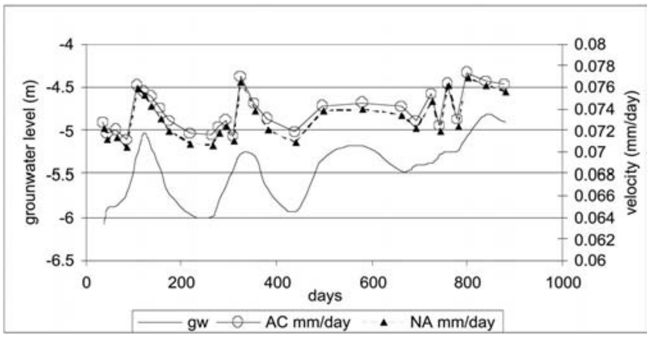

FIG. 8 - Calculated velocities with the AC- and NA-model in relation to measured groundwater fluctuations of the Monestier-du-Percy landslide in the period 23.11.1992-24.08.1995.

AN EXPLANATION FOR THE MORE SENSITIVE RESPONSE OF MEASURED VELOCITIES TO GROUNDWATER FLUCTUATIONS

Fig. 9 shows the relation between the velocities calculated by the AC- and NA-model and the observed mean velocities for different periods which are based on the observed inclinometer displacement in that period.

Fig. (9) shows the observed velocities having larger amplitudes than the ones calculated on the basis of the observed groundwater heights. Since all the calculations were done assuming a Bingham rheology (b=1 in Eq. (3)) the

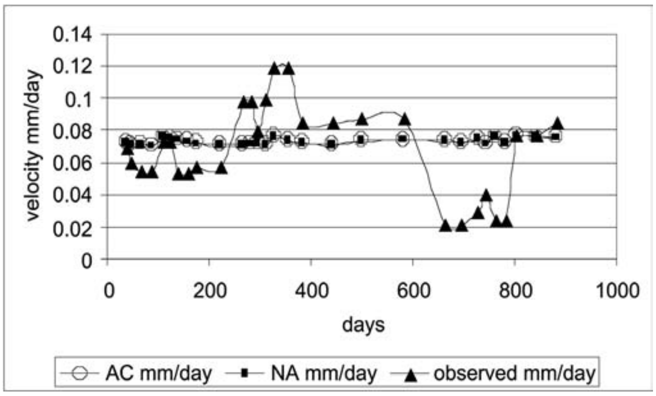

FIG. 9 - The relation between the velocities calculated by the AC- and NA-model and the observed mean velocities based on periodically measured inclinometer displacements on the Monestier-du-Percy landslide between 23.11.1992-24.08.1995.

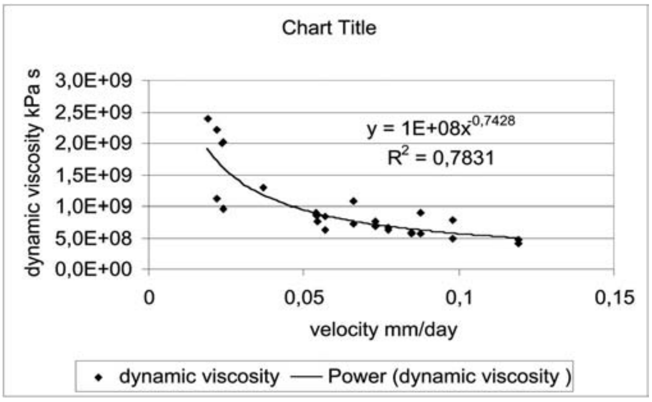

FIG. 10 - The relation between the back calculated viscosities in relation to the observed mean velocities calculated on the basis of inclinometer displacements measured on the Monestier-du-Percy landslide for each observation period between 23.11.1992-24.08.1995.

deviations between calculated velocities and observed velocities may be explained by a non linear relation ship between viscosity and excess shear stress as suggested for instance by the Herschel-Bulkley model and for slow moving landslides by Cartier and Pouget (1988), Salt (1988), Vulliet and Hutter (1988), Bracegirdle & *alii*, 1991, Conforth and Vessely 1991 Niewenhuis 1991. It may be caused by a rate dependent viscosity. Eq. (5) can be simplified to elucidate the relation between excess shear stress (τ_{excess}) on the one hand and the shear strain rate and dynamic viscosity on the other hand Eq. (11):

$$\tau_{excess} = \eta\left(\frac{\partial u}{\partial z}\right)^{b} \tag{11}$$

Equation 11 can be written, following Eq. (3), as a rate dependent viscosity assuming a linear velocity profile with a discrete velocity u over the shear band thickness (d) Eq. (12a):

$$\text{where} \quad \eta = \lambda u^{-b} \tag{12a}$$

$$\lambda = \tau_{excess} d^{b} \tag{12b}$$

Given the measured displacement for each observation period and the mean observed groundwater level we were able to back calculate with the NA-model a viscosity for each observation period. Fig. 10 gives the back calculated viscosity in relation to the observed mean velocity for each measuring interval. A relation between these two can be described with a trend line according to Eq. 12a, which deliver an exponential value for $b = 0.74$ with $R^2 = 0.78$ (see fig. 10).

The above described rate dependent viscosity can also be interpreted as an apparent viscosity, which consist of an intrinsic (constant) viscosity and a rate dependent excess pore pressure (Nieuwenhuis 1991). To calculate this excess pore pressure a constant intrinsic viscosity was assumed in this case, which we obtained as was shown before, by back calculation over the total test period (see table 1) We used the NA-model, since the difference in results with the AC-model could be neglected. Using this viscosity and the other parameters given in table 1, the virtual groundwater levels were back calculated using the observed displacement for each interval. These virtual groundwater levels may be related to excess pore pressure development. By subtracting the observed groundwater levels from the back calculated virtual groundwater levels, negative and positive deviations in groundwater levels were obtained, which could be transferred into positive and negative excess pore pressures in terms of kPa. These values are depicted for the different measuring intervals in fig. 11 in relation to the measured groundwater levels. There is a tendency that with a rising limb of the groundwater level excess pore pressure tends to go in a positive direction and with a falling limb pore pressure tends to go into a negative direction. There is no uniform reaction of excess pore pressure with the amplitudes of the measured groundwater levels.

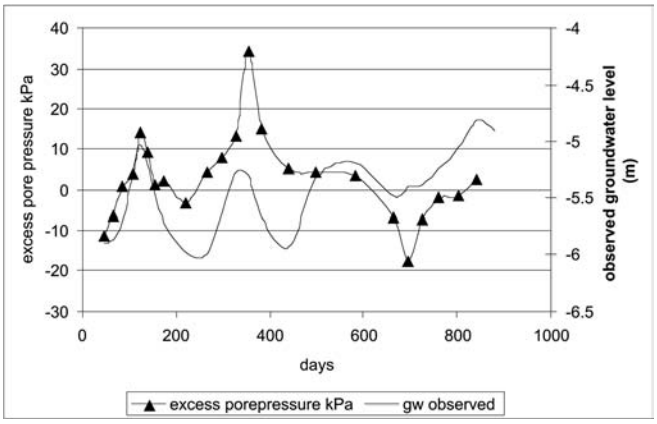

FIG. 11 - Back calculated excess negative and positive pore water pressures in relation to observed groundwater fluctuations during movement of the Monestier-du-Percy landslide in the period between 23.11.1992-24.08.1995.

DISCUSSION AND CONCLUSIONS

The Monestier-du-Percy landslide is a typical example of a slow-moving and deep-seated landslide developed in varved clays. The landslide moved over a long time period with varying (also zero) velocity. Over longer periods, a temporally attenuating trend in the amount of displacement seems to be observed at least for the North Eastern part of the Monestier-du-Percy landslide. The overall decrease in velocity may be caused by an increase in the overall safety factor controlled by a loss of mass in the upper part of the landslide. This must have an impact on the mean displacement rates over time.

The displacement profiles in both landslides show a relative thin deformation zone of maximum 1 m in thickness which can be thinner, impossible to detect due to the stiffness of the inclinometer tube.

Two models based on the equation of motion were tested on these displacement profiles. The AC-model uses all the terms including the local and convective acceleration terms. The NA-model ignores these terms making it a sort of steady state model. Hypothetical scenarios with instantaneous rising and lowering groundwater levels show differences in the onset to the new velocity, adapted to the new groundwater level: The NA-model shows an instantaneous reaction while the AC-model shows an acceleration and deceleration path towards the new steady state situation. However for slow moving landslides, differences between the two models can be neglected in the real world where the groundwater is rising and falling more gradually as could be observed during the test period.

Back calculation of the viscosity for each measuring period shows an exponential relation ship between excess shear stress and shear strain rate as expressed in the Herschel-Bulkley model for rapid moving debris flow but also suggested by many authors for slow moving landslides. It may be explained by a rate dependent viscosity. However one may also consider it as apparent viscosity, controlled by the generation of excess pore pressure reacting on changes in shear velocities. It is decreasing or increasing in excess the effective stresses during respectively deceleration and acceleration phases. An apparent rate dependency of the viscosity may also be explained by an increase or decrease of the shear band (d) during respectively acceleration and deceleration of the landslide. The Eqs. 6 and 7 and Eqs. 10a show, a positive correlation between shear band thickness (d) and the velocity u which is independent from the pore pressure ratio r_u (see Eq. 4. The calculated excess pore pressures in fig. 11 tend towards positive values with a rising limb of the groundwater and towards negative values with a lowering limb. This means that velocities increase above the ones related to neutral pore pressures for a. rising limb and towards lower values than what may be expected with neutral pore pressures, for a lowering limb. This may explain the hysteresis in the velocity pattern for rising and falling limbs of groundwater levels, found by Giusti & *alii*, (1996), Malet (2003), Van Asch (2005).

REFERENCES

Angeli M.G., Gasparetto P. & Bromhead E. (2004) - *Strength-regain mechanisms in intermittently moving landslides.* Proceeding IX th International Symposium on Landslides. Rio de Janeiro, vol. 1. Taylor and Francis, London, 689-696.

Antoine P., Giraud A. & Montjuvent G. (1981) - *Les argiles litées du Trièves; conditions de glissement et exemples de propriétés géotechniques*. Bulletin de la Société Géologique de France, 23(2), 117-127.

Baum R. & Fleming R.W. (1991) - *Use of longitudinal strain in identifying driving and resisting elements in landslides*. Geological Society America Bulletin, 103, 1121-1131.

Begueria S., van Asch Th.W.J., Malet J-P. & Grândahl S. (2009) - *A GIS-based numerical model for simulating the kinematics of mud- and debris flows over complex terrain.* Natural Hazards Earth System Science, 9, 1897-1909.

Bonnard Ch., Noverraz F., Lateltin O. & Raetzo H. (1995) - *Large landslides and possibilities of sudden reactivation.* Felsbau, 13 (6), 401-407.

Bracegirdle A., Vaughan P.R. & Hight D.W. (1991) - *Displacement prediction using rate effects on residual strength.* In: Bell (ed.), «Landslides, Proceedings of the VIth International Symposium on landslides». Christchurch Balkema, Rotterdam, 343-347.

Caron Ch., Leteltin O. & Raetzo H. (1996) - *Réactivation catastrophique du glissement de Falli-Hölli.* Quaternaire, 7, 111-116.

Cartier G. & Pouget P. (1988) - *Etude du compartement d'un remblai construit sur un versant instable. Le remblai de Sallèdes (Puy de Dôme).* Report N° 153, Laboratoire Central de Ponts et Chaussée, Paris.

Comegna L. & Picarelli L. (2005) - *The interplay between pore pressures and slope movements in fine-grained materials.* In: Barla G. & Barla M. (eds.), «Proceedings 11th Int. Conf. of the International Association. of Computer Methods and Advances in Geomechanics (IACMAG)». Turin, 3, 497-504.

Conforth D.H. & Vessely D.A. (1991) - *Factors of safety during landslide movements.* In: Bell (ed.), «Landslides, Proceedings of the VTth International Symposium on landslides». Christchurch Balkema, Rotterdam, 367-374.

Corominas J., Moya J., Ledesma A., Rius J., Gili J.A. & Lloretl A. (1999) - *Monitoring of the Vallcebre landslide, Eastern Pyrenees, Spain.* Proceedings International Symposium on Slope Stability Engineering, IS-Shikoku '99. Matsuyama. Japan, 2, 1239-1244.

Giraud A., Antoine P., van Asch Th. W.J. & Nieuwenhuis J.D.(1991) - *Geotechnical problems caused by glacio-lacustrine clays in the French Alp.* Engeneering Geology, 31, 185-195.

Giusti G., Iacarino G., Pellegrino A., Russo C., Urcioli G. & Picarelli L. (1996) - *Kinematic features of earthflows in Southern Apennines, Italy.* In: «Proceedings of the 7th International Symposium on Landslides». Trondheim, Norway, 1, 457-462.

Goren L. & Aharonov E. (2009) - *On the stability of landslides: A thermo-poro-elastic approach.* Earth and Planetary Science Letters, 277 pp., 365-372.

Iverson R.M. (2005) - *Regulation of landslide motion by dilatancy and pore pressure feedback.* Journal of Geophysical Research, 110, F02015, doi:10.1029/2004JF000268.

Keefer D.K. & Johnson A.M. (1983) - *Earth flows-morphology, mobilisation and movement.* U.S. Geological Survey Professional Paper, 1264.

Klubertanz G., Laloui L. & Vulliet L.(2000) - *On the use of multiphase modelling to simulate the initiation of slope movements.* In: «Proceedings of the 8th International Symposium on Landslides». Cardiff, UK, 2, 831-836.

Malet J.-P. (2003) - *Les glissements de type écoulement dans les marnes noires des Alpes du Sud. Morphologie, fonctionnement et modélisation hydro-mécanique*. PhD Thesis in Earth Sciences, Université Louis Pasteur, Strasbourg, 364 pp.

MALET J.-P., VAN ASCH TH. W.J., VAN BEEK L.P.H. & MAQUAIRE O. (2005) - *Forecasting the behaviour of complex landslides with a spatially distributed hydrological model.* Natural Hazards Earth System Science, 5(1), 71-85.

NIEUWENHUIS J.D. (1991) - *Variations in the stability and displacements of a shallow seasonal landslide in varved clays.* Balkema, Rotterdam, Thesis Utrecht, 144 pp.

NOVARAZ F., BONNARD CH., DUPRAZ H. & HUGUENIN L. (1998) - *Grands glissements et climat*. Rapport final PNR 31. Vdf, Zurich, 314 pp.

PICARELLI L., RUSSO C. & URCIUOLI G. (1995) - *Modelling earthflows based on experiences.* Proc.11th European Conference on Soil Mechanics and Foundation Engineering, Copenhagen, Danish Geotechnical Society 6, 157-162.

SALT G. (1988) - *Landslide mobility and remedial measures*. In: C. BONNARD (ed.), «Landslides Proc. of the Vth International Symposium on Landslides». Lausanne, Balkema, Rotterdam, 757-770.

VUILLERMET E. (1992) - *Caractéristiques géotechniques des argiles glaciolacustresdu Triéves*, PhD Thesis, University Joseph Fourier, Grenoble, 1992.

VULLIET L. & HUTTER K. (1988) - *Viscous-type sliding laws for landslides*. Canadian Geotechnical Journal, 25, 467-477.

VAN ASCH TH. W.J., HENDRIKS M.R., HESSEL R. & RAPPANGE F.E.(1996) - *Hydrological triggering conditions of a landslide in varvedclays in the French Alps*. Engineering Geology, 42, 239-252.

VAN ASCH TH. W.J. (2005) - *Modeling the hysteresis in the velocity pattern of slow-moving earthflows: the role of excess pore pressure*. Earth Surface Processes and Landforms, 30, 403-411.

VAN ASCH TH. W.J., MALET J.-P. & VAN BEEK L.P.H. (2006) - *Influence of landslide geometry and kinematic deformation to describe the liquefaction of landslides: some theoretical considerations*. Engeneering Geology, 88(1-2), 59-69.

VAN ASCH TH. W.J., MALET J.-P., VAN BEEK L.P.H. & AMITRANO D. (2007a) - *Techniques, advances, problems and issues in numerical modelling of landslide hazard*, Bulletin de la Societè Géologique de France, 178, 65-88.

VAN ASCH TH. W.J., VAN BEEK L.P.H. & BOGAARD T.A. (2007b) - *Problems in predicting the mobility of slow-moving landslides*. Engeneering Geology, 91, 46-55.

VAN ASCH TH. W.J., MALET J-P. & BOGAARD T.A. (2009) - *The effect of groundwater fluctuations on the velocity pattern of a slow-moving landslides*. Natural Hazards Earth System Science, 9, 739-749.

VAN GENUCHTEN P.M.B. & VAN ASCH TH. W.J. (1988) - *Factors controlling the movement of a landslide in varved clays near La Mure (French Alps)*. Bulletin de la Société Géologique de France, 8(4), 461-469.

VAN GENUCHTEN P.M.B. (1989) - *Movement mechanisms and slide velocity variations of landslides in varved clays in the French Alps*. Netherlands Geograph. Stud. n° 98, KNAG, Utrecht. Thesis Utrecht, 160 pp.

(Ms. received 1 January 2010; accepted 1 January 2011)