MODELLING THE FREQUENCY OF SHALLOW LANDSLIDES IN THE TERRES NOIRES REGION OF BARCELONNETTE

INTRODUCTION

In the basin of Barcelonnette (France) many shallow landslides (4-8 m) have developed in morainic or colluvial material which cover the slopes of the Jurassic marls (Terres Noires). The activity of these landslides is not so frequent compared to the more continuous seasonal movements which were measured in the shallow landslides of the varved clays area. Dendrochronological research (van Steyn & Van Asch) revealed moving incidents with a frequency of 10 - 12 years.

In the framework of the Epoch project a hydrological model was developed which can explain the frequency pattern of movements of these type of slides and elucidate the most important factors controlling the hydrological triggering system.

Hydrological field monitoring started already before this project but could be continued due to the support of the EPOCH project in order to get more insight in the hydrological structure of the water balance of these type of landslides.

On the basis of these results a hydrological model was developed, which describes the ground water fluctuation in relation to precipitation. These ground water fluctuations can be used as input in a stability model in order to assess the frequency of surpassing the threshold value of the Safety Factor within a certain time period. The calculated moving incidents can be calibrated with measured moving incidents obtained by dendrochronological research.

SITE DESCRIPTION AND INVESTIGATIONS

The investigated landslide lies in the Riou-Bourdoux Valley, a tributary of the Ubaye river situated about 4 km northwest of Barcelonnette.

Bedrock in this area consists of highly erodible Jurassic clayey black marls, (Terres Noires) on the lower part of the slopes and chalky Flysch (Eocene Nappe with dark marls at its base) on the higher parts. During the Weichselian glaciation parts of the Terres Noires and Flysch were covered with morainic material.

Auger drillings and soil profile pits have revealed that the displaced landslide mass consists of a mixture of Terres Noires marls which are weathered to varying degrees.

The examined slope has been reforested with pine trees. In contrast to the trees on the stable part of the slope, most trees on the landslide body are slanted and many trees eventually fell down.

The geophysical investigations (resistivity and seismic refraction measurements) indicate that the depth to the impervious Terres Noires marbles varies between 4 and 9 m. Furthermore the data show that there exist an upper layer with many cracks of about 2 m.depth could be observed during the Geophysical measurements that there is a relatively moist layer close to the bedrock, while the rest of the landslide body mainly consists of unsaturated material.

Hydrological field investigations were carried out partly before and within the Epoch project to analyze the processes governing the water flow in the investigated slope. (Caris and Van Asch 1991) Soil profile pits within the landslide body revealed that during wet periods moisture was concentrated in macropores whereas the interior of the aggregates was drier. In this case the macropores are formed mainly by shrinking cracks going down to a maximum depth of 1.5 m and to a lesser extent by pores formed by the soil fauna and by plant roots.

At the landslide body several well defined locations were found where water is slowly seeping to the ground surface even after several days without rain. The water infiltrates again at the immediate vicinity of these small seepages. It has also been noted that under wet conditions some boreholes would fill almost completely with water within a day whereas other boreholes remained dry. Once, during heavy rainfall, water was observed to flow out of a pipe in the main head scarp of the landslide.

All these observations illustrate that macro pores provide a means for rapid water transport in the upper 1.5 m of the landslide. According to Kirkby (1988), these non-capillary voids may behave as a dendritic network. These voids carry a high proportion of the total hill slope flow towards a relatively small number of discrete seepage lines, which are difficult to recognise.

Since the amount of macro pores rapidly decreases between 1 m and 1.50 m depth, a rapid decrease in vertical permeability can be expected which favours the development and persistence of a perched water table (Weyman, 1973) inhibiting quick percolation deeper into the landslide body. The same system was observed in the landslide bodies in the varved clay region.

The saturated hydraulic conductivity is an important parameter in the hydrological modelling. The inverse auger hole method was used in this case to measure the saturated hydraulic conductivity (Ksat) at two different depth intervals during a relatively dry period without water flowing into the boreholes. The principle of the auger hole test above the water table consists of boring a hole to a given depth, filling it with water, and measuring the rate of fall of the water level (I.L.R.I., 1974). The results are summarized in Table 3 .(Caris and Van Asch 1991)

depth (m)	n	Ksat (cm/day)	Sksat (cm/day)
0.3-0.8	11	15.7	12.0
1.5-2.0	8	0.7	1.5

Table 3: Mean value and standard deviation of saturated conductivity for two depth intervals as determined with the inverse auger hole method

Note: in four other boreholes no measurement was possible due to the quick fall of the water level in the upper half of the boreholes

In four boreholes the water level fell so fast that it was impossible to measure the rate of fall of the water level. This illustrates the importance of the macro pores on the saturated hydraulic conductivity. The Wilcoxon's two sample tests with a significance level of 0.001 was carried out to the measured Ks values, ignoring the results of these four boreholes. These tests showed that the saturated hydraulic conductivity from 0.3 to 0.8 m depth is significantly higher than from 1.5 to 2.0 m depth. Below two meters a decreasing trend in permeability due to increasing compaction of the soil material with depth may be expected.

To produce a reliable estimation of a saturated conductivity of the upper layer with macro pores the cube method of Bouma and Dekker (1981) was used. An additional advantage of this method is that it measures horizontal and vertical Ksat separately, whereas the inverse auger hole method measures an undefined mixture of horizontal and vertical flow components.

A cube of soil (25 x 25 x 25 cm) was carved out in situ and covered with gypsum according to the cube method. A vertical Ksat was measured by infiltrating water into the exposed upper surface and collecting it below the exposed lower surface of the cube. Bouma and Dekker suggest that the Ksat in two directions (vertical and horizontal) can be measured in the same sample. However, in the field it gave too many problems. Therefore, to measure the horizontal Ksat separate samples were carved out and then turned and covered with gypsum. In this case, the Ksat measured vertically represents the horizontal Ksat of the cube in its original position in the soil. The results (Table 4) illustrate the high permeability in a vertical and down slope direction of the upper layer with macro-pores.

Much lower values of Ksat were measured with the inverse auger hole method. Since the amount and dimensions of the macro pores decrease with depth, the lower values resulting from the inverse auger hole method can partially be explained by the larger depth interval over which Ksat is measured (0.3-0.8 versus 0.25-0.5 m (with the cube method). This is especially true considering that the top 80 cm was not homogeneous, because the root zone (the layer with 80% of the roots) was found lying between 0.4-0.6 m (Mulder and Van Asch, 1988). Furthermore, extremely high flow velocities observed in four inverse auger hole measurements could not be taken into account because no Ksat.values could be determined from these four tests.

Hor. Ksat (cm/day)	Vert. Ksat (cm/day)
150	6376
397	23

Table 4: Horizontal and vertical Ksat from 0.25 to 0.50 m as determined with the cube method in four different samples

It may be concluded that the cube method gives the correct values of the Ksat in the root zone whereas the inverse auger hole method yields correct values of Ksat for the layer without macro pores from 1.5-2 m. However, to give a correct value of the Ksat for the layer from 0.5 to 1.5 m extra measurements will be necessary.

The main conclusion is that a significant decrease in permeability occurs in the upper 1.5 m and that the permeability of this upper layer is mainly controlled by macro pores.

An oversized hole (0 = 5 cm) was drilled to the required depth to install the tensiometer (max depth = 6 m). The tensiometer was then lowered into the borehole. Afterwards, the hole was filled with dry loess up to a depth of 5 cm above the cup to ensure:

- good hydraulic contact between the soil and the cup and
- sufficiently unsaturated hydraulic conductivity during high water tensions.

After pouring water on the loess the hole was sealed by backfilling the lower part of the hole with bentonite grains. The upper part of the hole was backfilled with the original soil material.

Measurements were taken in May 1989 and from May to July 1991 (this project). Depending on the amount of rain the tensiometer measurements were made at an interval of several days.

The results of tensiometer measurements carried out in 1991 and 1992 shows a wet upper layer up to a depth of 1.5 which dries slowly. The upper layer is underlain by relatively dry soil which is gradually becoming wet. There is only slow vertical drainage of water due to the extremely low unsaturated hydraulic conductivity of the dry subsoil, despite the large hydraulic gradient between the upper layer and the subsoil. The results of the measurements taken at a depth of 6 meters indicate that towards the bedrock the soil becomes moister again, which was also proved by the resistivity measurements. If the soil at 6 m is in equilibrium with a water table then this water table is found at a depth of about 7.5m. This depth coincides with the geophysical data.

THE HYDROLOGICAL MODELLING

Within the framework of this project the geophysical and hydrological results obtained before and within this project were used to develop a three layer model of the landslide: a high permeable fissured top layer of 1.5 metre; a second layer of 4-6 metres with a low saturated hydraulic conductivity and a third layer consisting of unweathered Terres Noires which is considered as impermeable. The slip surface is assumed to have developed at the boundary of layer 2 and 3. The hydrological model which will be discussed here is simple because only monthly precipitation data during 25 years were available. Also the hydrological parameters which were measured in the field are still limited. (Saturated hydraulic conductivity and pF curves of the soil material). Therefore as a first attempt a conceptual water balance model was developed describing the amount of water storage in the different layers.

Figure 17. gives a flow chart of the model. As an input for this model the water storage model of Thornthwaite and Mather(1957) is used. This model describes the water balance in the root zone on a monthly base according to the following balance equation:

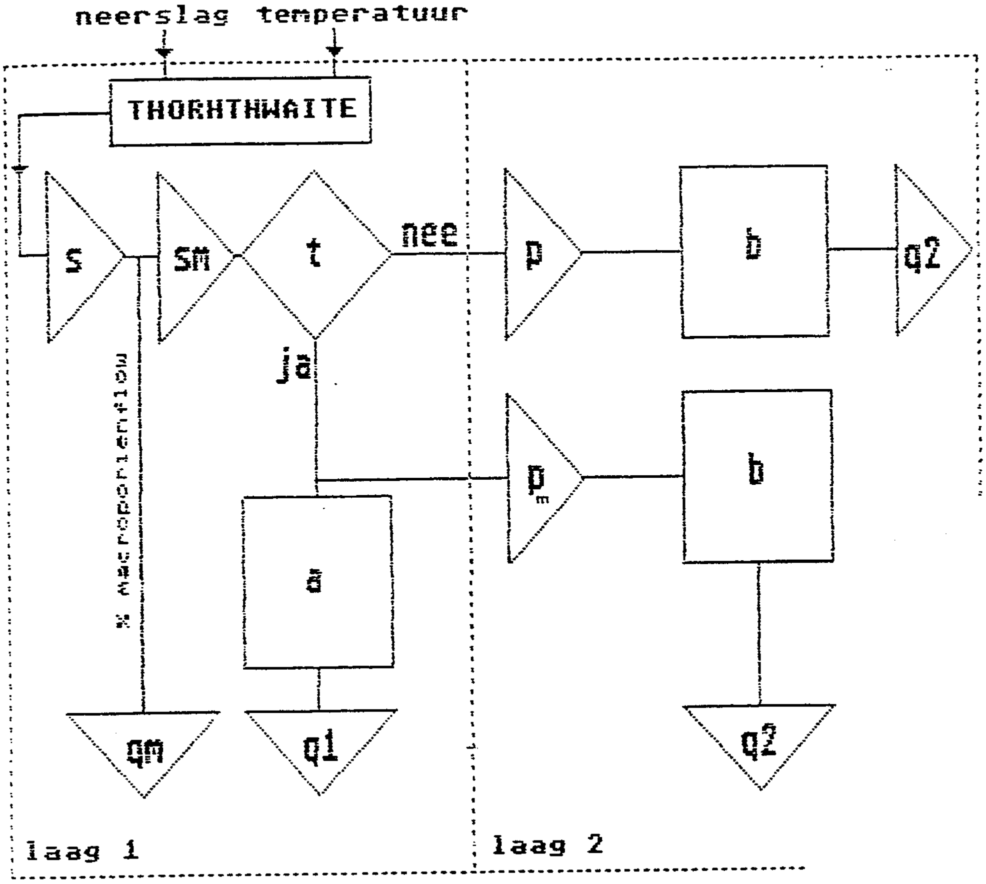

Figure 17 Flow chart of a two layer hydrologic model for shallow landslides (8 m) in Terres Noires colluvium

$$P = AET + \Delta SM + S \tag{26}$$

in which
P = precipitation (mm)
AET = actual evapotranspiration,
ΔSM = soil moisture storage in the rootzone
S = water surplus percolating downward from the root zone.

The Thornthwaite model is thus a water filter on top of the model described in figure 4. The amount of water surplus S will percolate into layer 2 towards the slip surface at the boundary between weathered and unweathered material. There is however a restriction indicated by the regulator t in figure. 17. If the calculated surplus S is greater than the maximum percolation per month (Pm) in the second layer the deficit (a) per month remains in the primary layer. The maximum percolation velocity and hence the maximum amount of percolation per month (Pm) is given by the Darcy equation:

$$Pm = [\Delta Ym + (\Delta Yz/\Delta z)] * Ksat \tag{27}$$

in which
Pm = percolation velocity (cm/day)
ΔYm = difference in matrix head (cm) calculated from pF curves of the soil
ΔYz = difference in elevation head (cm)
Δz = distance (cm)
$Ksat$ = saturated hydraulic conductivity measured in the field (cm/day).

The calculations give the amount of "initial" storage per month in the two layers. It was assumed that the third layer of unweathered Terres Noires is impermeable. A second step to calculate the net storage per month is to subtract from the initially calculated storage in the two layers the amount of lateral flow (q1 and q2). This lateral flow is calculated also according to Darcy's law. The gradient of the total head is given by the slope angle of the phreatic surface which is assumed to be the mean topographical slope angle of the landslide.

The model has also an option to subtract an amount of direct loss in the first layer by lateral flow through the large fissures. The calculations give per month an amount of water depth in cm in the different layers which can be translated to ground water height by calculating the amount of available pore space. This is considered as the difference in water content between saturated and field capacity conditions of the soil.

SIMULATION OF THE TEMPORAL (IN)STABILITY OF THE SLIDE

The estimated ground water height per month within the landslide, calculated according to the above given model, gives the possibility to calculate the Safety Factor of the slide per month. This can be done by classical stability models. Because of the flat configuration of the slide the Janbu model was used. It appeared that the difference in Safety Factor values between the simplified Janbu method and the rigorous method was very small. Therefore the simplified method was used for saving calculation time. The stability model needs the configuration of the slope and the slip surface which was detected by the geophysical methods and the geotechnical characteristics of the landslide material.

For the calculation it was assumed that the slip surface has residual strength characteristics. The safety factor was calculated per month using the calculated ground water heights per month from the hydrological model in the second layer for the period 1956-1980. It appeared that the Safety Factor never reach the critical value of 1 (instability) in the 25 years -period of simulation, while dendrochronological investigations did show several moving incidents within this period. One important failure in the modelling may be the two dimensional approach. Field observations showed that the landslide has also a lateral influx of water into the sides of the slide which probably seems to be important.

In the model it was assumed that the second layer has no fissures. In reality there may exist major fissures which are connected with the slip plane and which can be filled with water increasing the pore pressure on the slip surface more rapidly. The model doesn't take into consideration the hydrological anisotropy which may be present in the secondary layer. This can not be measured with the augerhole method and it was technical impossible to take cubes (for the cube method) from a depth of more than 2 metre. A greater Ksat. in the vertical direction (due to fissures) than the horizontal direction may result in higher ground water heights.
Therefore the Ks value in the second layer were calibrated in such a way that peaks of the calculated safety factor values reaches the value of 1 in the 25 period of simulation.

Figure 18 shows the results of the calculated safety factors which are related to the calculated ground water heights calculated with the calibrated hydrological model. The figure also indicate the years of moving events which were identified by the dendrochronological research. It shows a rather good correlation with the peaks of the safety factor values reaching the value of 1. The figure shows that between 1956 and 1980 there are two periods with probably moving incidents: around 1960 and a period without sharp peaks between 1970 and 1980.

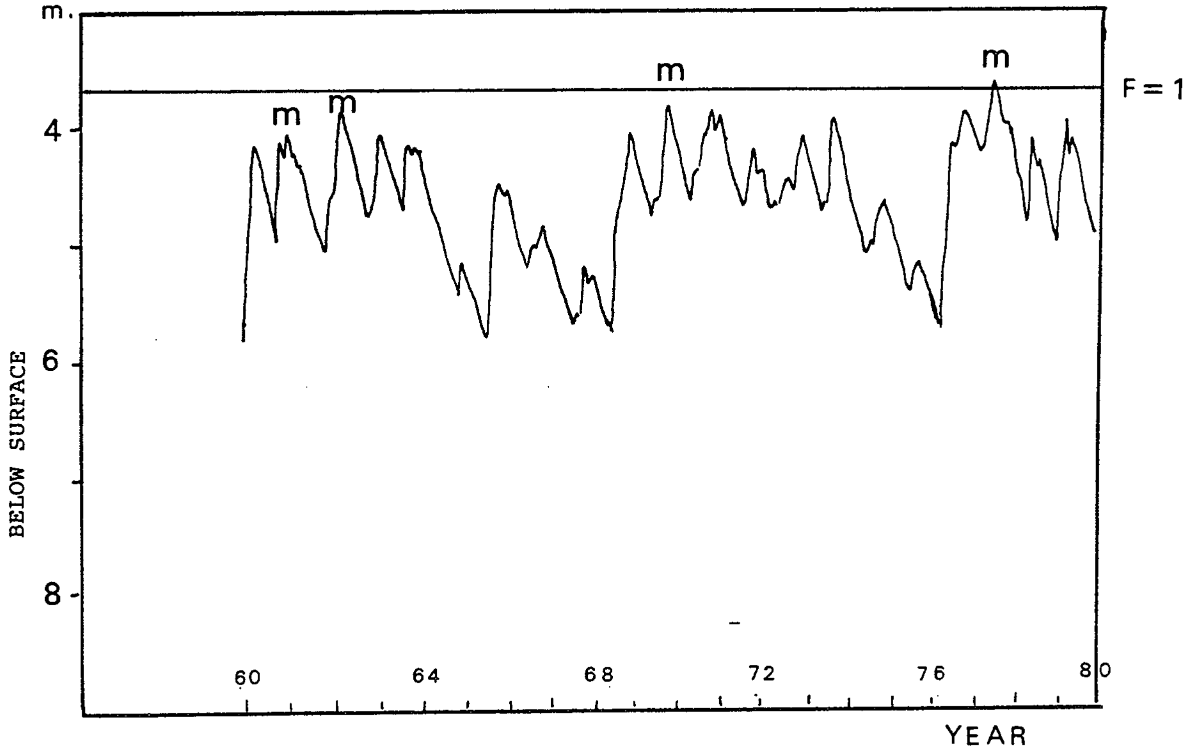

Figure 18 Moving incidents dated by dendrochronological methods (m) against simulated groundwater fluctuations and related safety factor for a landslide in Terres Noires Colluvium.

DISCUSSION AND CONCLUSIONS

The geophysical and hydrological investigations of this typical landslide in the Terres Noires region show that most moisture concentrates in the upper layer with desiccation cracks and in the zone close to the bedrock. Because the relatively dry poorly permeable intermediate layer (roughly from 1.5 to 4-9 m) is situated underneath the rooting zone and above impervious bedrock the high water tensions encountered in this zone can only be explained by the low water fluxes in this layer. The data show that at the same time relatively fast subsurface run-off of excess rainfall occurs within the highly permeable upper 1.5 m of the landslide body in which a perched water table may occur.

The hydrological modelling which is based on field observations and measurements gives an estimate of ground water heights per month which can be linked to a Safety Factor per month using stability calculations and assuming a state of residual strength along the slip surface. The hydrological modelling did not result in an instable condition in the period of 1956 - 1980 whereas there are strong indications, based on tree ring observations, that instability has occurred in this period. This means that the model and the hydrological parametric values give no realistic absolute values but only indications of relatively critical periods. The measured Ks has to be calibrated within the hydrological model in order to get failure in the periods which are indicated as failure periods by the dendrochronological research. This is ascribed to the two dimensional character of the model neglecting lateral water concentration and the effect of fissures in the subsurface giving the subsoil an anisotropic character with a relatively higher Ks values in a vertical than in a horizontal direction.

The field measurements and the modelling shows long term fluctuations of the phreatic surface of the ground water taking several months to half a year. This is due to the relative low water fluxes in the second layer and the high drainage capacity of the top layer. Therefore short-term heavy rains are not effective because most of the water will rapidly be transported down slope through the upper layer. Only during long-term wet conditions (months or even years) with limited evapotranspiration the slow vertical drainage can be maintained causing eventually instability.
The hydrological investigations and modelling show evidently that the placing of interception drains in the permeable upper 1.5 m of the landslide is possibly a sufficiently preventive measure against reactivation, since without the infiltration from the upper layer, no critical pore water pressures can build up above the basal slip plane.

What are the lessons to be learned from this experiment?
- It is very difficult to assess the precise values of the hydrological parameters by field measurements. The results can be used to describe the differences in hydrological characteristics between different layers and to develop a concept for hydrological modelling.
- To get insight in the hydrological structure of the landslide direct measurements of

the pore pressure fluctuations within different layers seems to be very effective.

- The characterisation of hydrological parameters for the different layers can be done most effectively by calibrating simple hydrological models with measured ground water fluctuations.
- If ground water data are not available over a longer period the use of dendrochronological techniques appeared to be very useful for modelling the frequency of landslide movement which are controlled by long term fluctuations of the phreatic surface. If the geotechnical characterisation of the landslide in terms of strength characteristics and the position of the slip surface are well known one can back analyze the ground water heights at which failure must occur. Dendrochronological research gives the possibility to date failure conditions and therefore to date the years in which peak heights have occurred. This dated peak heights can be used to calibrate hydrological models relating ground water fluctuation to precipitation.