A stochastical approach to landslide hazard determination in a forested area

Approche stochastique pour la détermination des risques de glissements dans une région forestière

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ABSTRACT: Spatial landslide hazard is determined in a forested area (French Alps) with steep slopes, consisting of gray marls, covered with morainic rmaterial. The cumulative probability that the F-value (safety factor) is lower than unity is calculated for different slope classes. The probability expressed as a percentage is compared with the spatial frequency of the number of landslides observed in the field.

RESUMÉ: Les risques spatiaux de mouvements de terrain ont été determinés dans une région forestière (Alpes Françaises) aux pentes raides, formées de marnes noires sous une couverture morainique. La probabilité cumulative pour le facteur de sécurité d'avoir un valeur moins qu'un a été calculée pour des differentes classes de pentes. Cette probabilité, exprimée en pourcentage est considerée comme un indice de risque, qui est comparé avec la fréquence spatiale du nombre de glissements observés dans le terrain.

1 INTRODUCTION

Landslide hazard can be defined according to Varnes (1984) as the probability of occurence of landslides within a specific period of time (temporal hazard) and within a given area (spatial hazard). Temporal landslide hazard is mainly determined by climatological and meteorological factors while spatial hazard is mainly determined by landscape factors. A few examples are available where temporal landslide hazard (a.o. Wu 1980) and spatial landslide hazard (a.o. Ward et al. 1982 Edil & Schultz 1983) are modelled in a quantitative way. The general aim of this type of modelling is to predict changes in landslide hazard which are caused by a change in hydrological and landscape factors due to human interference. A more quantitative approach of hazard prediction might be useful for planning and management activities in a certain region.

In this paper special attention is focused on the assessment of spatial landslide hazard. Modelling of this type of hazard can be done by means of conventional equilibrium models and the spatial variability of the parameters of these models. The variability of these parameters results in a certain distribution of safety factor values around unity. This can be considered as a measure for the probability of landsliding for a certain point or area in the landscape. The distribution of the safety factor (F), which might be a measure for landslide hazard, can be determined for each point in a grid system using spatial interpolation techniques (Webster 1985, Burrough 1986) for the estimation of the values of the model parameters at each grid point. One can also calculate the distribution of safety factor values for a certain landunit, which is a priori diliniated according to one or more specific parameters (like e.g. slope angle, rock-soil type etc.). The chosen strategy depends on the spatial variability structure of the parameters of the equilibrium model. It is therefore important to get insight within reasonable time and costs in the spatial variability of the most sensitive parameters of the model. This can be done by the use of semivariograms (Burrough 1986, Mulder & Van Asch 1988).

The main question which has to be answered with respect to this type of modelling is whether the calculated cumulative probability that the safety factor $F < 1$ for a certain point or landunit has a certain correlation with the spatial frequency of observed landsliding in the field. If such a correlation excists, the model might be suitable for the prediction of a change in hazard, due to a change in certain landscape parameters.

The question is discussed in this paper, where a spatial landslide hazard analysis is set up for a forested area of the Riou Bourdou near Barcelonnette in the French Alps. Especially in forested areas it is necessary to make a good quantitative estimate of all positive and negative effects of the forest cover on slope stability activities. (A short description of the area is given in Van Asch & Mulder 1988).

2 LANDSLIDE HAZARD MODELLING

For the determination of the slope stability in terms of a safety factor (F), the infinite slope stability model for planar slides was used in which the effect of rootstrength can be inserted in terms of a cohesion term. Also the surcharge of trees has been taken into account. One can write the equilibrium equation in the following form. Gray & Megahn (1981):

$$F = \frac{\dfrac{(2\,Cs + Cr)}{\gamma_w H \;\; \sin 2\beta} + \left[\dfrac{q_o}{\gamma_w H} + \left(\dfrac{\gamma_{sat}}{\gamma_w} - 1\right) + \dfrac{\gamma}{\gamma_w}\left(1 - M\right)\right]\dfrac{\tan\varphi}{\tan\beta}}{\dfrac{q_o}{\gamma_w H} + \left(\dfrac{\gamma_{sat}}{\gamma_w}\right)M + \dfrac{\gamma}{\gamma_w}\left(1 - M\right)}$$

M= relative height of phreatic surface = $\frac{Hw}{H}$

From the equation we can learn that the following parameters have to be measured in the field: H(m) = thickness towards potential slipsurface, which means thickness of a soil layer with specific soil mechanical characteristics; Hw(m) = height of piezometric surface above potential slipsurface; Cs(kNm^{-2}) = effective cohesion of soil; Cr(kNm^{-2}) = shear strength increase from root reinforcement expressed as cohesion (kNm^{-2}); γ (kNm^{-3}) = density of moist soil above piezometric surface (kNm^{-3}); γ_{sat}(kNm^{-3}) = saturated density of soil (kNm^{-3}); γ_w = (kNm^{-3}) density of water; q_0(kNm^{-3}) vertical surchange from weight of trees; β (degrees) = slope angle; φ : (degrees) = angle of internal friction. The following strategy is proposed in order to limit the number of measurements:

1. Attention will be focused on those parameters influencing in the most sensitive way the stability of the slope (F-value).

2. For the most sensitive parameters a sample scheme is needed in order to assess the sample density and the spatial trend and variability structure of these parameters.

ad 1. Sensitivity analyses which hereherto has been carried out for planar slides in forested area's (Gray & Megahan 1981, Ward et.al. 1982) revealed that for shallow soils the most important parameters are slope angle, groundwater height, strength parameters (C and φ and depth towards slipsurface (Gray & Megahan 1981, Ward et.al. 1982).

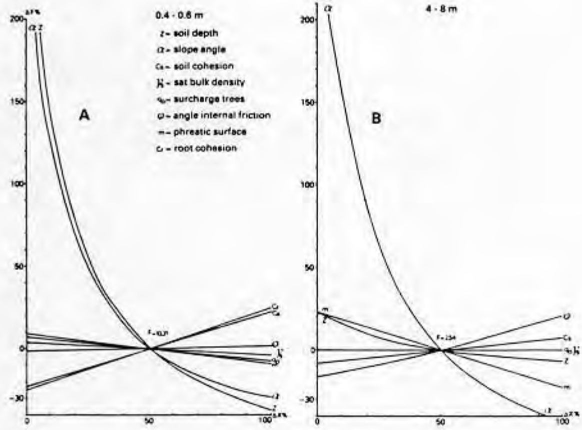

Figure 1. The sensivity of the input variables in the infinite slope stability model Percent change in safety factor (F) versus percent change in input variables for the rootzone (A) and the total morainic cover (B).

Fig. 1 shows the results of sensitivity analyses carried out for the morainic soils in the Riou Bourdou. In order to measure the influence of each parameter the median value of all other measured-parameters was put into equation (1) while the value of the parameter under consideration was increased stepwise from its minimum value to its maximum value. The sensitivity analyses were carried out for two depths of the soil profile: from ± 0.4-0.6 m, which is the depth of the root zone and from 4-8 m which is the variation in the depth of the morainic cover. Fig. 1 shows that slope angle is a very sensitive parameter, while the strength parameters and the groundwater height parameter have medium influence on the F-value. Mind also that the depth of regolith, surcharge of trees and bulkdensity parameters become relative unimportant for deeper soil layers (fig. 1B). Fig. 1A also shows that the rootzone has a median F-value of 10.3, which means that the probability of soil slipping of this layer is neglectable.

Ad 2. It is possible to construct a hazard map on the basis of a grid system, where for each point a probable F-value can be calculated which is based on the probability of values of the individual parameters for eacht point. These grid point values, can be derived from spatial interpolation techniques of the individual parameters. It appeared however that there excists no spatial trend and correlation of the variability with distance between points for the most sensitive parameters (Mulder & Van Asch 1988). This means that the best estimate of a value of the most sensitive parameters in one point is the usual mean computed from all sample points of the total area. Therefore it was decided to make a zonation of the area according to the most sensitive parameter in casu the slope angle (see fig. 1). Within each zone it was assumed that the variation of the other parameters is the same as for the total area. For the assessment of the degree of hazard, the variability of the F-value for each slope zone was calculated by means of the Monte Carlo method (Benjamin and Cornell 1970). In order to do this one must look at the variability and distribution of the parameters of the equilibrium model. The measurements of the strength and bulkdensity parameters revealed a normal distribution (Mulder & Van Asch 1988). For the other (less) sensitive parameters like surcharge of trees, also a normal distribution was used in the Monte Carlo system. There are few figures available about the depth of the morainic cover. This parameter is necessary to calculate the chance for sliding over the total depth of the morainic cover assuming that there is no relation of strength with depth Borings on measuring plots and exposures in "terres noires" badlands revealed that the morainic cover has a minimum thickness of ± 4 metres and a maximum thickness of ± 8 metres. Therefore we introduced in to the Monte Carlo calculations a uniform distribution of the depth of the total regolith of 4-8 metres.

Fig. 2 gives the stability of the slope in relation to slope angle class and different classes of groundwater depth below the slope surface. The variation of slope angle and groundwater depth within each class is assumed to be uniform in the Monte Carlo calculations.

Fig. 2A gives the mean F-values of the rootzone in which no part of the distribution of these F-values lies below unity. Therefore there is no chance that the rootzone will slip away. It should be noted that we introduced for the rootzone a total cohesion value supplied by soil and rootstrength together, which is determined by 70 unconfined compression tests and 20 direct shear test carried out on samples with various root contents. It appeared that the measured total cohesion doesn't differ significantly from the cohesion measured in the soil below the root zone (Mulder & Van Asch 1988). One explanation might be the fact that in the root zone the overconsolidated strength of the morainic material in terms of a cohesion is reduced to zero by the activity of the roots and burrowing animals, but this is more or less compensated by the cohesive strength given by the root structure. This important factor needs however further research.

Fig. 2B gives the chance of soil slipping of the total morainic cover taking into account that there is no relation of soil strength with depth below the root zone (see Mulder & Van Asch 1988). Therefore it is assumed that the slipsurface develops at the base of the morainic cover. The chance of slipping is expressed here as a cumulative probability that the F-value is less than unity (vertical axis). The probability percentage is given again in relation to slope and groundwater classes and is considered to be representative for different slope angle classes and groundwater heights in the Riou Bourdou. Fig. 2B shows that their are (real chances for deeper landslides under the worst hydrological conditions (completely saturated profile) and for the steepest slope classes $> 25°$. The figure shows that also groundwater is a crucial factor and the real dangerous spots are those where groundwater reaches the soil surface.

Fig. 2C gives the chance of a slipping of the top soil (root zone) in case of a removal of the forest. In this simulation of landslide hazard it is assumed that the total cohesion of the rootzone reduces to zero because of a complete decay of the roots and the cohesion of the soil material of the rootzone is zero (see above). If these assumptions are true figure 2C shows an expected real chance for slippig of the topsoil in the steepest slopes ($>25°$) with groundwater depths of less than 1 metre.

Fig. 2D shows that the effect of a removal of the forest on the stability of the total morainic regolith with a thickness of 4-8 metres is very limited from a

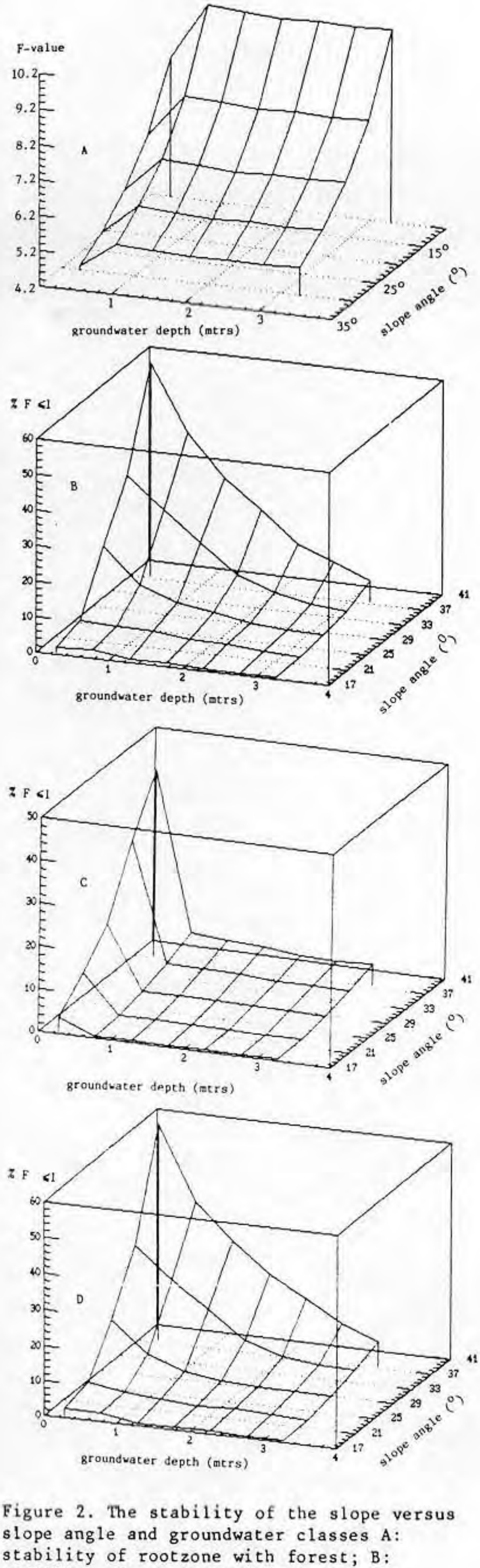

Figure 2. The stability of the slope versus slope angle and groundwater classes A: stability of rootzone with forest; B: stability of total morainic cover with forest; C: stability of rootzone after removal of forest; D: stability of total morainic cover after removal of forest; F-value is mean safety factor; % F ≤ 1: cumulative probability that the F-value is less than or equal to unity.

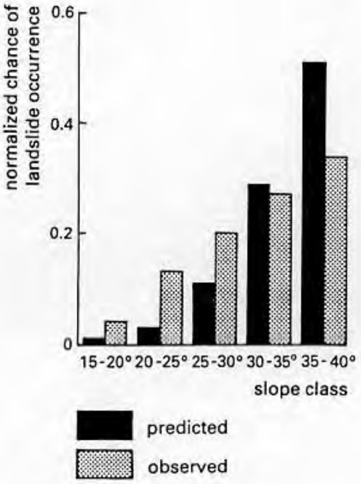

Figure 3. A comparison between the normalized distribution over five slopeclasses of the cumulative probability of sliding (% F ≤ 1) and the normalized distribution of the number of landslides per unit area.

mechanical point of view, because:

a. The removal of the surcharche of trees has practically zero effect on the stability of these relative deep slides (see fig. 1B);

It is interesting to compare such a conservative calculation of hazard with the frequency of landsliding found in the field. Therefore in fig. 3 the normalized distribution over five slope classes of the cumulative probability of sliding (%F ≤ 1) is compared with the normalized distribution of the number of landslides per unit area. The figure shows that the predicted relative chance of sliding is probable too low for the lower slope classes and too high for the higher slope classes. It might be concluded that the distribution of maximum groundwater levels cannot be considered independently from the slope angle. Obviously, lower slope angle classes give relative higher maximum groundwater levels than higher slope angle classes.

b. Apart from the fact that the roots has both positive and negative effects on the total strength of a layer (see above) there are practically no roots in the soil below 1 metre;

c. A removal of the forest might increase the maximum groundwater conditions due to a decrease in interception and evapotranspiration. Assuming an increase in groundwater height of one class (± 50 cm) (see eg WU 1980) there is an increase in landslide hazard varying from ± 6-12% for the steepest slope classes (see fig. 2D).

An indication of the maximum groundwater height within the different slope class zones in the field might give more precise information about landslide hazard as can be deduced from fig. 2. This can be done by introducing simple spatial groundwater models relating input of rain slope and groundwater heights (see Wu 1980, Okimura & Kawatani 1986).

One can also choose for a risk map based on the conservative assumption that groundwater will reach once the groundsurface at all places in the landscape. In fact the time axis is neglected in the hazard analyses, which means that the spatial frequency of landslide hazard is determined over an infinite long period.

CONCLUSIONS

The prediction of a change in landslide hazard in relation to all sort of planning and management activities in the landscape, must be done by means of slope stability models. Because of the great spatial variability of the parameters of these deterministic models, only a probability of slope failure can be determined for a certain landunit. This stochastic, approach is suitable for areas with a simple homogeneous geomorphological and geolological structure and for a single type of slope failure.

In the Riou Bourdou drainage basin many slopes consist of a morainic cover (4-8 m) underlain by "terres noires" marls. In the morainic cover landslides have developed, which can be described by the infinite slope stability model. For the assessment of a hazard zonation it was desirable to subdivide the landscape into units according to slope classes, because slope angle proved to be a very sensitive parameter for equilibrium conditions and this parameter is easy to map in the field. A comparison of the calculated degree of spatial hazard with the actual spatial frequency of sliding reveals an underestimate of the calculated hazard for the lower slope classes and an overestimate for the higher slope classes. A greater accuracy of spatial hazard will be achieved in future research by the introduction of groundwater models, relating slope angle to the spatial distribution of maximum groundwater levels.

A simulation of the removal of the forest showed that on steep slopes the (cohesionless) top soil (rootzone) might slip away. The change in hazard for deeper slides (towards a depth of 8 metres) is rather limited (in the order of five to ten percent).

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