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Prediction program for slow moving landslides

Programme de prédiction des glissements de terrain à déplacement lent

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ABSTRACT: The deformation behaviour of large, slow moving landslides is often governed by rainfall characteristics. Whereas the average deformation rate per year of such landslides is often in the range of some mm to several cm, permanent deformation measurements for instance by means of permanently installed chain inclinometers show a far wider range of deformation rates especially after dry or very wet periods. If in addition to chain inclinometers, a weather station and permanent measured pore water gauges in the slip zone are installed one can identify in many cases a strong correlation between strong rain fall events, a time-delayed increase of the pore water pressure in the slip zone and simultaneously to this, an increase of the deformation rate of the landslide. So, based on these data, a good understanding of the above-mentioned correlation can be obtained. In this paper a newly developed analytical model which couples the relation between rainfall characteristics and the development of pore water pressures in the slip zone on one hand and the deformation behaviour of the slope on the other will be presented. The code allows a partition of the landslide in different sections to consider the often-observed time delayed deformation behaviour over the length of large landslides. The interrelation of shear resistance in the slip surface and deformation rate is defined by a logarithmic constitutive law. The calibration of the model is done by means of the above-mentioned permanent measurement data of precipitation, pore water pressures and deformation measurements.

RÉSUMÉ: Le comportement de déformation des grands glissements de terrain à déplacement lent est souvent régi par les caractéristiques des précipitations. Alors que le taux de déformation moyen par an de ces glissements de terrain est souvent compris entre quelques mm et plusieurs cm, les mesures permanentes de la déformation, par exemple au moyen d'inclinomètres à chaîne installés en permanence, montrent une gamme beaucoup plus large de taux de déformation, en particulier après des périodes sèches ou très humides. Si, en plus des inclinomètres à chaîne, une station météorologique et des jauges permanentes de l'eau interstitielle sont installées dans la zone de glissement, on peut identifier dans de nombreux cas une forte corrélation entre de fortes chutes de pluie, une augmentation différée de la pression de l'eau interstitielle dans la zone de glissement et, simultanément, une augmentation du taux de déformation du glissement de terrain. Ainsi, sur la base de ces données, une bonne compréhension de la corrélation susmentionnée peut être obtenue. Cet article présente un nouveau modèle analytique qui associe la relation entre les caractéristiques des précipitations et le développement des pressions d'eau interstitielle dans la zone de glissement, d'une part, et le comportement de déformation de la pente, d'autre part. Le code permet de diviser le glissement de terrain en différentes sections afin de prendre en compte le comportement de déformation souvent observé avec un décalage dans le temps sur la longueur des grands glissements de terrain. L'interrelation entre la résistance au cisaillement dans la surface de glissement et le taux de déformation est définie par une loi constitutive logarithmique. L'étalonnage du modèle est effectué à l'aide des données de mesure permanentes susmentionnées concernant les précipitations, les pressions de l'eau interstitielle et les mesures de déformation.

Keywords: Landslide; creep; inclinometer; pore water pressure; deformation rate.

1 INTRODUCTION

The deformation behaviour of large, slow moving landslides are often governed by rainfall and/or snow melting but sometimes also by man-induced processes. Such slow moving landslides (SMLS) are a common phenomenon in Alpine regions and their origin is often connected with erosion processes by glaciers during the last Ice Age, when steep mountain slopes have been left after the melting of the glaciers about 10.000 to 15.000 years ago. As a consequence, some of these steep mountain slopes developed to instable and large landslides, with low deformation rates in mm to cm per year and low factors of safety (FOS) (Marte & Hofmann 2020).

When infrastructure such as motorways, tunnels, railway tracks, water power plants, snow water storages on mountain slopes or constructions with a severe damage potential in general are endangered by such SMLS, an extensive assessment of the deformation behaviour, safety aspects as well as the future behaviour of the slope is required (Leroueil, 2001; Hungr, 2016). Typical questions are (Marte, 2019):

- What is the expected deformation behaviour of the SMLS which needs to be considered for the life cycle of the objects?
- What is the "FOS" of the SMLS and how does it influence endangered objects?
- What are circumstances which could lead to a sudden failure of the SMLS?
- Is a sudden failure of the SMLS predictable and what is a proper observational instrumentation?
- What kind of remediation measures are applicable – what are their effects and their costs?

To work out proper answers for such questions geological survey (field work and subsoil exploration) and extensive measurement campaigns (e.g. inclinometer, geodetical, ground water resp. pore water measurements, installation of a weather station) are generally implemented (Ausweger, 2018, Marte & Hofmann, 2020). Based on results and data from this investigation geological, geotechnical and calculation models are developed. SMLS show in many cases complex geometrical and geological boundary conditions, a long history and often large movements in past as well as sometimes different triggers which govern the deformation behaviour. For such complex landslides – in many cases only simplified calculation models which prove to be valid only for some of the questions and aspects above, are available. Therefore a critical interpretation of calculation results is essential.

Improved calculation models allow a direct comparison of calculation results with measured data, which also allow a calibration of the most important input data. When for instance a calculation model delivers deformation (rate) and/or pore water pressures in the slip surface as results, this data can directly be compared to measurement data (Ausweger, 2018). On the other hand, a calculated FOS is a number which cannot be measured or controlled directly in the field, at most a change in FOS can be quantified indirectly by a change of deformation rate of the SMLS.

In the next chapter a new developed analytical model which couples the relation between rainfall characteristics, the development of pore water pressures in the slip zone and the deformation behaviour of the slope is presented. The model is calibrated on the bases of measured deformation and pore water pressure data over a longer period of time.

2 MODEL FOR SLOW MOVING LANDSLIDES

The presented model has been developed for SMLS, which are mainly triggered by rainfall (and snow melting) events. The primary input data therefore are precipitation data from a weather station (or artificial rainfall data for future events). The model is a combination of a hydrogeological model and a simple mechanical creep model (Leinenkugel, 1976). The hydrogeological model allows the calculation of pore water pressures along the slip zone over time as a function of the rainfall data. The mechanical creep model is used to calculate the deformation rate of the slope as a function of time and of pore water pressures in the slip zone.

2.1 Model description

The analytical model is based on the infinite slope model with an expansion that the SMLS is subdivided into several blocks, with the active earth pressure *Ea* at the upper end and a mobilisation function for the earth resistance *Er* at the lower end of the SMLS as shown in Figure.1 and Figure 2. The whole slope is split up into multiple finite blocks. Each block is a trapezoid with a vertical height at the lower end t_1, a vertical height at the higher end t_2 and a horizontal length l (Figure 1).

Additionally the inclination α of the slip plane is given. With that the geometry of each block is determined.

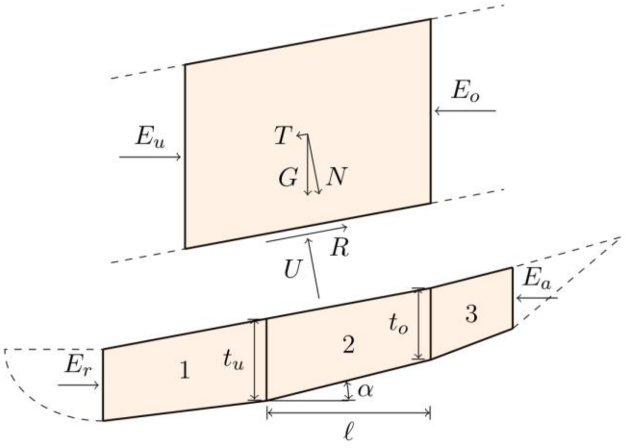

Figure 1. Model basics.

The model in the longitudinal section is shown in the lower part of Figure 1. A material is assigned to each block. The most important properties of the material are the weight γ to calculate the dead load *G* and with the geometrical data *N*, and *T* the normal and tangential component of *G*. Further input data are the friction angle Φ, the stiffness *E* and the creep index *Iv*.

The creep index *Iv* is a value that stems from the model after (Leinenkugel, 1976). The forces acting in the blocs are shown in the upper part of Figure 1:(*R* … shear resistance in the slip surface; *Eu* and *Eo* … Earth pressure at the lower and upper end of the bloc; *u* pore water pressure in the slip surface and *v* average deformation rate in a bloc). The number of blocs as well as the inclination of the surface and slip surface of each single bloc in the model is chosen individually for each SMLS. In the actual version the bloc stiffness is modelled by a Young's Modulus *E*, and the Poisson ratio is chosen v=0, so the mechanical model can be seen as 1D model.

In this model the main mechanism that controls the deformations and velocity of the slope are the pore water pressures in the slip plane as well as the characteristics of the earth resistance and the mobilization function at the lower end respectively. A change in the pore water pressure results in a change of shear resistance and further on the velocity.

Each block has 5 degrees of freedom in the model. The general velocity of the block, the earth pressure force and the displacements on the the lower and upper side . The system of equation is split into 5 equations for the 5 degrees of freedom. The central equation (1) is the relationship between the changing forces at one block and the change of velocity:

$$(\Delta E_o - \Delta E_u) * \cos\alpha + \Delta u * \frac{l}{\cos\alpha} * \tan\phi - \tau_0 * I_v * \ln\left(\frac{v_i}{v_{i-1}}\right) * \frac{l}{\cos\alpha} = 0 \qquad (1)$$

The first term describes the change of the earth pressure forces on the end of the blocks in direction of the slip plane. The second term describes the change of the resisting force in the slip plane due to a change of the pore water pressure. The last term describes the change of the resisting force due to the change of velocity whereas I_v is the creep index according to Leinenkugel (1976).

The second leading equation formulates the change of the length of each block by $(\Delta S_o - \Delta S_u)$ the difference in displacements at the upper and lower end of a bloc) due of the changes of stress in the blocks $(\Delta E_{o,i}, \Delta E_{u,i})$ This is approximated with Hook's law:

$$(\Delta S_o - \Delta S_u) * \frac{\cos\alpha}{l} * E - \frac{1}{2}\left(\frac{\Delta E_u}{t_1} + \frac{\Delta E_o}{t_2}\right) = 0 \qquad (2)$$

The third major equation describes the relationship between the change of displacements of the blocks in direction of the slip plane and the velocity of each bloc:

$$v_i * \Delta t - \frac{\Delta S_o + \Delta S_u}{2\cos\alpha} = 0 \qquad (3)$$

And the last two field equations connects the change of earth pressure and change of displacements between two consecutive blocks:

$$\Delta E_{o,b} = \Delta E_{u,b+1} \qquad (4)$$

$$\Delta S_{o,b} = \Delta S_{u,b+1} \qquad (5)$$

To finish the system of equations two boundary equations are necessary. For the bottom boundary a mobilization function that combines the displacements of the lowest joint with an according earth pressure.

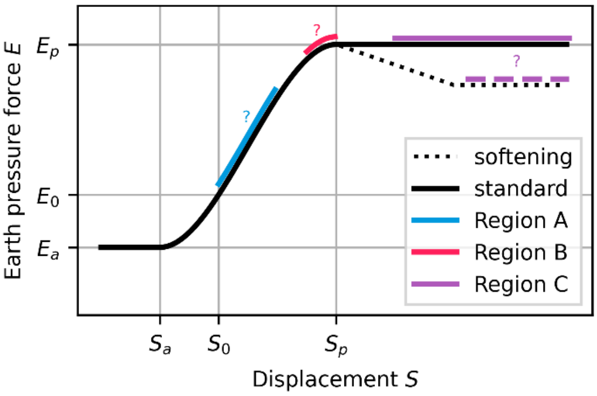

Figure 2. Mobilization Function for Er.

The mobilization function (Figure 2) is approximated as a polynom of third order that ranges from the active earth pressure E_a at the lower bound to the passive earth pressure E_p at the higher bound with a horizontal tangent at each point. The respective displacements s_a, s_0 and s_p in Figure 2 are calibration parameters of the model. The starting point on this function is another important initial parameter of the model and is understood as a representation of the history of the landslide. Region A (blue) in Figure 2 as starting point for the simulation shows a young SMLS with only small deformation in the past whereas Regions B and C show a SMLS with significant deformation in the past. Region C indicates two scenarios, one without softening and one with softening behaviour at large deformation.

In Figure 3 the principles of the hydrogeological model are presented for one single bloc which can be understood as a tank-like element. There are two types of such tank-like elements. The standard type that is modeled after the blocks in the Geomechanical Model and a source area element. The standard element takes the geometric properties of the block like the length, height and inclination. Other material properties like porosity *n*, saturation *Sr* and hydraulic conductivity *kf* are added in the model to model the discharges through the block. Other properties are tuning factors for the amount of infiltration and influx that flows into the block from the sides. These elements are thought as 1m wide. The source area element, which describes the catchment area above the landslide, on the other hand has the same material and infiltration properties but has only an area and an inclination as geometric properties. In difference to the standard elements the source area element has two different flows out. One is the flow above the slip surface into the next bloc-element. To calculate the outflow into a 1 m wide bloc element the width of the bottom of the source area is given. The other outflow is below the slip surface that flows out of the system and does not inflence the behaviour of the SMLS anymore.

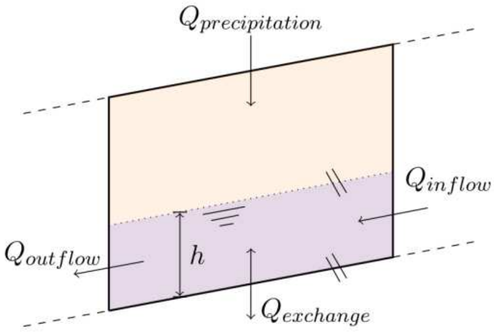

Figure 3. Hydrogeological Model.

$Q_{precipitation}$, Q_{inflow}, $Q_{outflow}$ respectively $Q_{exchange}$ in Figure 3. show water input and output in one bloc element.

So the model simulates a cascade of bloc elements in the direction of the slope. With the input of precipitation data the volume of water as well as a fictive water level in the elements, the flow between the elements and the pore water pressure in the slip surface is simulated. The cascade starts with the source area element from which the first flow to the top most block element is simulated. Further on an inflitration into each bloc element occur over the surface. At the bottom of the slope the discharges just flows out of the system.

For the simulation an initial water level is assigned for each element. This water level is then calculated into a volume with the length of the block, the porosity and the degree of saturation of the material.

Now every time step this volume is updated with the given flows between the elements and the infiltration over the surface and the new water level is calculated. As the system is a linear system of equations the whole calculation can be written in matrix form and solved with common linear system of equation solvers. The pore water pressures for each elemement are then saved as input for the Geomechanical Model.

2.2 Initial values and calibration parameters

To calculate the system a number of initial values have to be chosen. The initial velocity of all the blocks needs to be given together with the past displacement of the bottom block in order to initialize the mobilization function. With the initial earth resistance at the bottom block and the active earth pressure at the top most block an initial distribution of earth pressures along the slope is calculated. By multiplying the calculated earth pressures with the respective joint heights the initial forces E_o and E_u can be calculated in each joint. These earth pressures are then used to calculate an initial total resisting force in the slip plane that results from the earth pressure forces and the weight of the block. With these information the system can be calculated.

The calibration of the model, i.e. the determination of the major input data is done by comparing the calculation results for a certain time period respectively the rain fall data for this period with available measurement data from permanent pore water pressure measurements (PW-gauges) as well as data from chain inclinometer(s). Main input data are adjusted until a proper curve fitting of calculated and measured data are achieved. In Figure 4 measurement data from a case history, which are used to calibrate the model for this SMLS are shown exemplarily. The programming code for the model is written in Python 3.

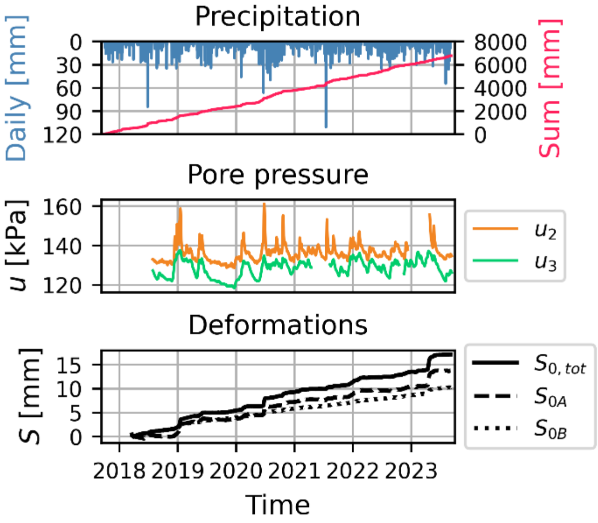

Figure 4. Measurement data for calibration of the model for a case history. Upper figure: Daily and cumulated precipitation data; Central figure: Measured pore water pressures in two points along the slip surface; Lower figure: Results (displacements) from an inclinometer measurement in different depths of the landslide.

3 CASE STUDY WITH ARTIFICIAL DATA

To present the general capacity of the model, Figure 5 shows the results of an artificial data set. A slope model with three blocks and a sinus shaped rainfall distribution over a time period of three years is modelled. The earth pressure E_r at the lower end is assumed to start with earth pressure at rest E_0 at time zero. The infiltration of water in the slope is assumed in this simplified example only from the catchment area above the highest bloc of the landslide.

The results of pore water pressures in the slip surface show in accordance to the modelled sinus shaped rainfall distribution also a sinus shaped distribution over the year, with highest and temporary first peaks in the topmost bloc where the water inflow occurs first. The deformation curves for the different blocs show the highest deformation (rates) in the uppermost bloc and the lowest deformation (rates) in the lowest bloc where earth resistance is the highest and increases with further deformation.

This can also be seen in the lowest chart of Figure 5, where the earth pressure development over the three years is presented. On the upper end of the model the earth pressure remain on the level of the active earth pressure (red line). On the lower end the earth resistence increase with ongoing deformation according to the mobilization function as shown qualitively in Figure 2.

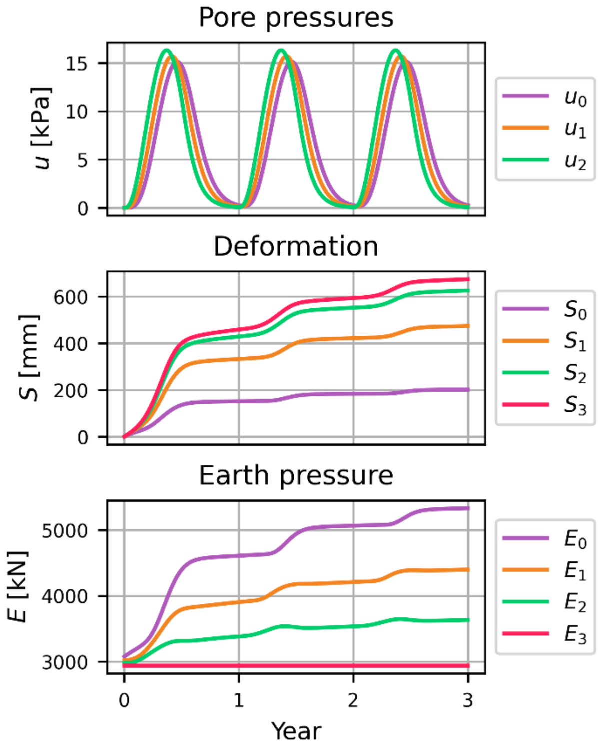

Figure 5. Calculation results for an artificial example.

It also can be seen that the same amount of pore water pressure peaks over the years lead to a decrease in ΔE over the time because of an increasing earth resistence with time. ΔE means the change of earth pressure in the bloc joints. E_3 in figure 5 is the constant active earth pressure at the upper end of the landslide, E_0 is the earth resistance (accorting to the moblization function) at the lower end of the landslide. E_1 and E_2 ar the earth pressures in the bloc joints of the model. This demonstrates the influence of the landslide history.

The application of the model for real case histories show on the one hand the applicablity and sgnificant improvements by the model compared to classical models with only discussing FOS. On the other hand the effort to get measurement data from chain inclinometers and permanent pore water pressure measurements in the slip surface as well as the challenge of a reliable calibration of the model specially for complex boundary conditions needs to be mentioned.

4 CONCLUSIONS

In this paper a combined hydrogeological-geomechanical model for slow moving large landslides is presented. For this type of landslides, the analytical model allows the simulation of the dependency of precipitation characteristics, time delayed pore water pressure developments in the slip surface and as consequence changes in the deformation rates. For slow moving landslides the model can be understood as supplement to classical analytical models which allow the calculation of FOS only. Assumed a successful calibration of the model is done, the prediction of further deformation behaviour as function of possible future rainfall events can be simulated. The model also is a good supplement for warning and alert plans, based on pore water pressure and deformation measurements, because a much deeper understanding of the deformation behaviour of the landslide is possible. Further developments of the model are necessary to simulate the influence of stabilization measures – such as anchors, dewatering measures but also the effect of pumping storages with changing water tables at the toe of such a SMLS.

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