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LANDSLIDES – RISK ASSESSMENT BY MODELLING THE SIGNIFICANT INFLUENCES LEADING TO FIRST-TIME FAILURE

André Arnold

Institute of Civil Engineering, Lucerne University of Applied Sciences and Arts, Switzerland. E-mail: andre.arnold@hslu.ch

Philipp Baechler

Impuls AG, Switzerland. E-mail: philipp.baechler@impulsthun.ch

The study of past landslide events shows that natural slopes typically fail during or after events of heavy precipitation. Certain areas of slopes appear to fail at random while other areas remain stable. This raises the question, as to whether a better assessment of the risk of a landslide event is possible and how to quantify the safety against failure. The focus on the development of near-surface landslides qualitatively shows which time-dependent parameters might play a role in the course of time until the first slope-failure. The relevant parameters are subsequently categorised into different predisposition classes: minimal to slowly changing predispositions with time (such as soil-grain size distribution, soil-layering, slope angle); significantly changing predispositions with time (such as saturation, peak friction angle) and triggering factors such as heavy rainfall or other impacts. The consideration of all parameters in a single model enables a risk analysis of first-time slope failure as a function of time. This implies that triggering factors may cause slope failure in a situation of higher risk due to stronger predispositions, whereas stronger triggering factors may not cause a failure due to lower predispositions being active in the slope. The predisposition model after Kraettli and Schwarz for the purpose of risk assessment of landslides is introduced. Subsequently, the application is illustrated in the practical example of a landslide site. First results of risk assessment and an outlook for further development of the model are discussed.

Keywords: landslides, triggering of mass movements, strain-softening, soil mechanics, unsaturated soil

1.Introductionand fundamental concepts

The study of past landslides shows that natural slopes typically fail during or after events of heavy rainfall (Askarinejad, 2013; Thielen, 2007; Latelin et al. 2001; Take & Bolton, 2013). Certain areas of slopes remain stable while others seem to fail at random. This article summarizes the findings of a master's thesis at Lucerne University of Applied Sciences and Arts, School of Engineering.

Basic soil mechanics in terms of slope stability analysis are described in e.g. Arnold et al. (2019) as follows: often the ordinary Mohr-Coulomb failure criterion (Coulomb, 1776) is considered to describe the shear strength in a slope at failure using the internal friction angle φ' and the cohesion c'. It is a common discussion (e.g. Arnold et al. 2019; Take & Bolton 2013; Atkinson 2007; Wood 1990) that once the critical state is reached due to larger shear strains in the soil, no cohesion c' is left. Peak states with $\varphi'_{peak} > \varphi'_{crit}$ may occur at smaller shear strains. This indicates that the parameter φ' in the Mohr-Coulomb failure criterion (Coulomb, 1776) is not constant for a specific soil as long as the critical state has not been reached.

Leroueil (2001) distinguishes between linear-elastic, non-linear-elastic and visco-plastic behavior and mentions that visco-plastic strains could even develop near yet within the yield-surface. Hence, visco-plastic behavior with strain softening can occur on the dry side of critical (Schofield and Wroth, 1968) without reaching a yield surface. Take and Bolton (2013) describe qualitative stress paths for water infiltration and the decrease of effective stress level in the soil (loss of suction). The stress paths are allowed to reach the dry side (described as "peak states" in Fig. 1) of critical, potentially resulting in strain-softening due to the loss of suction and consequently in the risk of slope failure.

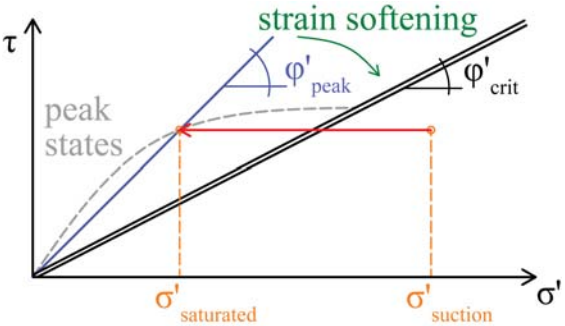

Fig. 1.Qualitative stress path for loss of suction and subsequent possibility of strain softening at dry side of critical (after Take & Bolton, 2013 (stress path) and Atkinson, 2007 (description of peak states)).

2. The Predisposition Model

Stability problems in natural slopes can often not be ascribed to a single and specific mechanism. Typically, many processes influence the stability of a natural slope during a specific period. A predisposition model (*PM*), as used by Kraettli and Schwarz (2015) and mentioned in Heinimann et al. (1998) and Liener et al. (1996), is a viable tool to place different time-dependent influences of slope stability issues in relation to each other. A schematic overview of the *PM* as used by Kraettli and Schwarz (2015) is provided in Fig.2.

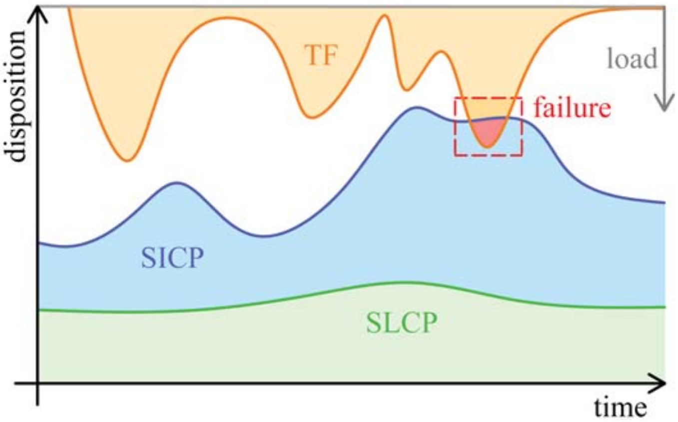

Fig. 2.Predisposition model (*PM*) after Kraettli and Schwarz (2015)

A distinction is made between (i) slowly changing predispositions (*SLCP*), (ii) significantly changing predispositions (*SICP*) and (iii) triggering factors (*TF*). The predispositions and their magnitude are related to each other and their overlap with the *TF* predicts potential failure as a function of time. The qualitative example illustrated in Fig.2 shows that comparatively large triggering factors in combination with small predispositions do not necessarily lead to slope failure, whereas larger predispositions could lead to the failure of a slope with relatively small *TF*.

The predisposition has a direct impact on the stability calculation. Considering the Janbu equation (Janbu, 1954, Eq (1)), the *SLCP* is located as the slope inclination α, whereas the *SICP* is located as the friction angle φ' which can vary as long as the critical state friction angle φ'_{crit} is not reached. The *TF* is considered to be a load, which might act horizontally (H) or vertically(V) (Eq. (1)).

$$F = \frac{(G+V) \cdot tan\,(\varphi') \cdot \frac{1}{n_\alpha}}{(G+V) \cdot tan\,(\alpha) + H} \qquad (1)$$

2.1.*Examples for different predisposition classes*

2.1.1.*Slowly changing predispositions (SLCP)*

SLCP (Kraettli and Schwarz, 2015) do not change significantly or only change very slowly over time or geological periods. Examples of such are soil composition or stratification. The slope inclination may have a significant influence on the slope stability, however, this parameter exhibits only minor changes over time.

2.1.2.*Significantly changing predispositions (SICP)*

SICP (Kraettli and Schwarz, 2015) are subjected to continuous change and will therefore have a strong influence on the slope stability. These predispositions are described for example in Take and Bolton (2013) as already mentioned in the introductory section. Take and Bolton (2013) showed continuous softening of a clay slope exposed to changing weather conditions (alternating dry and wet conditions) due to loss of suction in a series of centrifuge model tests. The clay soil exhibited continuous softening in wet conditions due to a stress path leading to the dry side of critical (Fig. 1). Therefore, the peak states for φ', as described in e.g. Atkinson (2007), decrease with consecutive wet periods, causing φ'_{max} to tend towards φ'_{crit}. Consequently, the predisposition will contribute to a larger extent to the slope instability as a cause of first time failure. The contribution of Take & Bolton (2013) shows that *SICP* might play a key role in the definition of the *TF* of a slope instability.

2.1.3.*Triggering factors (TF)*

A *TF* (Kraettli and Schwarz, 2015) is described by short-term changes in load caused for example by heavy rainfall on a natural slope. Another example is the formation of cracks on a slope crest such as are shown in Fig. 3. Once such cracks fill with water - typically due to rainfall - the slope might become unstable as a result of the water pressure acting on the slope crest. Another *TF* could be a surface flow of water resulting in triggering forces on the slope surface.

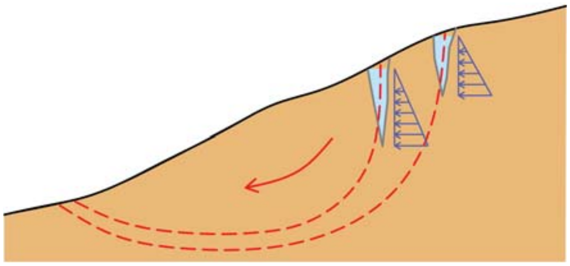

Fig. 3.Natural slope with water-filled cracks on the slope crest.

3. Analysis of alandslide site

A landslide in Sachseln, a town in central Switzerland (Rickli, 2001), was analyzed qualitatively with the *PM*. Some soil structure details as well as geological background are described in Rickli (2001). The slope was formed towards the end of the last ice age in which glaciers melted and some ground moraine material with coarser grains remained. Weathering processes steadily increased the silt- and clay content in the soil. In August 1997, an event of intense precipitation constituted the *TF* for an ensuing slope stability problem in the area. The approximate geometry of one of the landslides in Sachseln is given in Fig. 4.

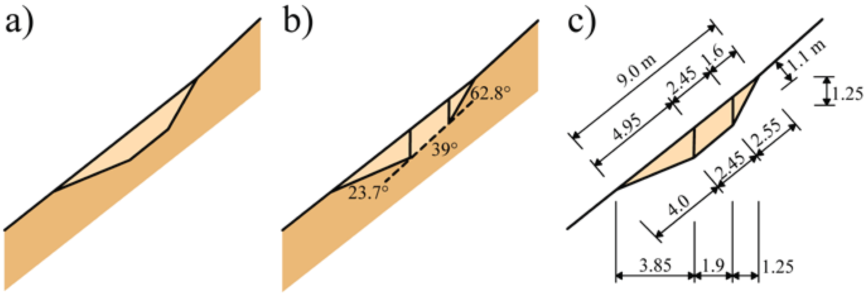

Fig. 4.Slope stability in Sachseln (1997): a) Approximate failure mechanism of landslide 605.01 (Rickli, 2001); b) Discretisation in slices for the Janbu (1954) calculation; c) Approximate dimensions of the failure mechanism and the corresponding slices. Dimensions are provided in [m].

The mean slope angle of $\alpha = 39°$ is identified as the *SLCP*, whereas the mobilised friction angle φ'_{mob} and the corresponding dependency of this parameter on suction effects is identified as the *SICP*. The intense precipitation and its effects in terms of horizontal and also vertical loads on the slope constituted the *TF*. The input parameters for the following analysis of the slope are provided in Table 1.

Table 1. Input parameters for the analysis of the slope stability

Parameter	Characterisation
Slope inclination α	39°
Pore water pressure u	variable
Peak friction angle φ'_{max} (assumption)	41°
Friction angle at critical state φ'_{crit} (Rickli, 2001)	33°
Horizontal force H due to surface discharge	variable
Vertical force V due to surface discharge	variable

4. Discussion

The development of mobilized friction angle with respect to time is illustrated in Fig. 5. Due to assumed alternating wet and dry periods, there would have been softening in terms of φ'_{mob} as described in Take and Bolton (2013). This results in increasing *SICP* with time (*B* and *E* in Fig. 5). Furthermore, the *SICP* would decrease with increasing suction during dry periods (*C* and *F* in Fig. 5). The *TF* are considered in a rudimentary fashion in the model and approximated as horizontal- and vertical loads. It may be assumed that different sections of a potential failure mechanism in a slope would exhibit different progressions of predispositions due to softening of φ'_{peak}. Hence, the quantitative softening behavior might depend on the geometry of the failure mechanism and the corresponding mobilized friction angle along the shear bands (Davies, 1981). The herein presented model might be able to more realistically predict why certain sections of a slope fail while others remain stable. In order to improve such a prediction, detailed information on possible failure mechanisms and the details of soil behavior in terms of softening are crucial.

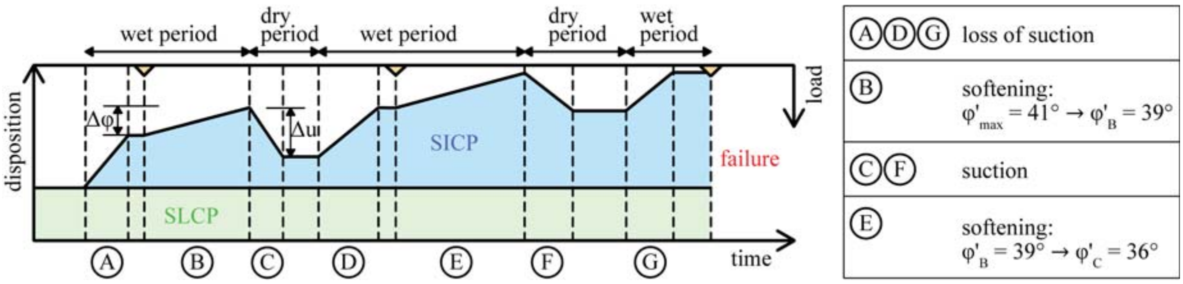

Fig. 5.Approximate development of predispositions with time for the Sachseln landslide (Rickli, 2001) based on calculations according to Janbu (1954). No phreatic level was assumed in the slope with saturated conditions.

5. Conclusions

The herein described *PM* could assist with the prediction of slope stability problems, provided that underlying parameters based on soil mechanics are more accurately quantified. Softening effects with alternating wet- and dry periods are of main interest and should be studied in more detail such as is described in the study by Take & Bolton (2013). The effect of precipitation on the stability of slopes in terms of loads should also be investigated. In conclusion, probabilistic approaches on the development of predispositions could also play an important role.

Site sampling and analysis of the in-situ strength-deformation behavior could provide insight into the safety of slopes under investigation. The *PM* gives quantitative information on the state of a slope, provided that in-situ strength and development with subsequent shear strains is described. This information would enable engineers and public authorities to significantly improve strategies for monitoring measures and interventions. Furthermore, this model approach raises awareness that soil strength as a parameter does not necessarily remain constant and is subject to change over time and with variable environmental conditions as introduced earlier with Fig. 5.

Currently, it remains challenging to assign different influences on slope stability problems to their suitable predisposition classes. The future development of the predisposition model with the goal to improve its informative value will be challenging, albeit a most important undertaking.

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