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Role of remolding energy in the post-failure movements of landslides

Rôle de l’énergie de remaniement dans les mouvements post rupture des glissements de terrains

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ABSTRACT: Studies by various researchers suggest that a knowledge about the complete stress-strain curves help in the assessment of the landslide potential of sensitive clays. The post-peak stress-stain behavior of sensitive clays particularly indicates the disintegration process in the material as well as helps in the estimation of the energy involved in the disintegration process. The energy concept is a subject of current study by several researchers working on investigation of flow slides on sensitive clays. Several terms such as degradation energy, strain energy or remolding energy have been used to indicate the energy available for disintegration of sensitive clays; this is referred to as remolding energy in this work and is simply defined as the strain energy involved in the disintegration or remolding of a material. A closer examination of the concept of remolding energy provides an understanding of the overall mechanical behavior of sensitive clays during landslides. In this paper, concept of remolding energy analytically proposed by the authors is elaborated in light of laboratory and field tests conducted to determine remolding energy of sensitive clays. Finally, an attempt is establish a correlation between the run-out distances and the remolding energy of the sensitive clays involved in a landslide event.

RÉSUMÉ : Les études de plusieurs chercheurs suggèrent que la connaissance, sur les courbes complètes de contraintes-déformations, aide à l’évaluation du potentiel de glissement des argiles sensitives. Le comportement post pic en déformation des argiles sensitives indique particulièrement que le processus de désintégration dans le matériau aide aussi dans l’estimation de l’énergie associée au processus de désintégration. Le concept d’énergie sujet de la présente étude l’a été pour plusieurs chercheurs travaillant sur l’investigation des coulées dans les argiles sensitives. Différents termes, tels que l’énergie de dégradation, l’énergie de déformation ou l’énergie de remaniement ont été utilisés pour indiquer l’énergie disponible pour la désintégration des argiles sensitives ; elle est désignée par énergie de remaniement dans le présent travail et est simplement définie comme l’énergie de déformation impliquée dans la désintégration ou le remaniement du matériau. Un examen plus poussé du concept de l’énergie de remaniement fournit une compréhension de l’ensemble du comportement mécanique des argiles sensitives durant les glissements. Dans cet article le concept d’énergie de remaniement proposé analytiquement par les auteurs est élaboré sous la lumière de tests in situ conduits pour déterminer l’ER des argiles sensitives. Finalement, une tentative est faite pour établir une corrélation entre la distance parcourue et l’énergie de remaniement des argiles sensitives impliquées dans le glissement.

KEYWORDS: Landslides, Sensitive clays, Remolding energy, Runout distance, Retrogression distance

1 INTRODUCTION

Rapid debris flows, debris avalanches, earth flows, sensitive clay landslides, rock avalanches and failures of loose fill and mining waste are among the most dangerous and most damaging of all landslide phenomena. Their runout determines a large portion of the consequences and the risk associated with the landslides. Runout parameters include the maximum distance reached, flow velocities, thickness and distribution of deposits, as well as the behavior in bends and at obstacles in the flow path. Sensitive clay landslides, occasionally fast moving landslide, involve massive soil volumes of the order of millions of cubic metres (e.g., Lacasse 2013; Hungr 2016; Strand et al. 2017).

Sensitive clays are mainly found in Canada, Norway, and Sweden. Sensitive clays are often categorized using the term sensitivity (S_t), which is the ratio between the undrained shear strength (c_u) measured in the intact state (c_{ui}) and the remolded (c_{ur}) sensitive clay using the fall cone method. Bjerrum (1955, 1961) demonstrated that highly sensitive clays may have salt contents as low as 0.5%, whereas marine clays commonly have salt contents of 3% or more. Sensitive clays transform from an intact state to highly viscous fluid when subjected to large deformation during landslides. The retrogression distance and runout distance resulted from such landslide are occasionally fast moving and involves massive soil volumes of the order of millions of cubic meters (e.g., Bjerrum 1955; Lacasse 2013; Thakur et al. 2014).

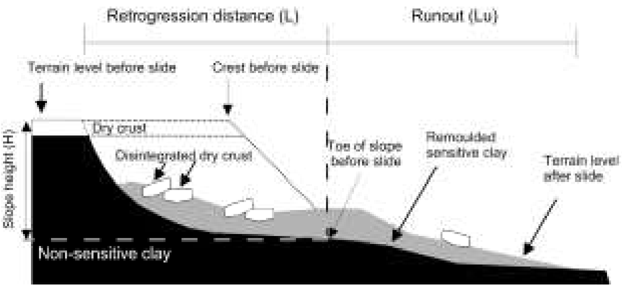

Figure 1. Schematic illustration of landslide in sensitive clays (Strand et al. 2017).

In literature, there exist several indicators of potential for flow slides of sensitive clay, e.g. the remolded shear strength (c_{ur}), the liquidity index (I_L), the sensitivity (S_t), the quickness (Q). Although these criteria are useful indicators of clay's potential to remold and then flow, these individual geotechnical parameters cannot be used to determine whether a landslide will actually occur or not. Another promising approach is to study the remolding process of sensitive clays. In other words, this demands an understanding of complete stress-strain behavior of sensitive clays. This paper attempts to illustrate the usefulness of the remolding energy approach to assess landslides in sensitive clays.

2 RECENT DEVELOPMENTS

Post-failure movements of sensitive clay landslides, in terms of retrogression distance (L) and the runout distance (L_u), are often evaluated using the geomorphology information based empirical approaches. Locat et al. (2008) proposed a correlation between the run-out distance and normalized slide volume (V/W_{avg}) for Canadian sensitive clays. Here V is the landslide volume and W_{avg} is the average width of landslide pit. The upper limit was given as follows:

$$L_u = 1.3\ (V/W_{avg})^{0.73} \quad (1)$$

$$L_u = 8.8L^{0.8} \quad (2)$$

Recently, Strand et al. (2017) proposed the following relationships based on the data from 51 sensitive clay landslides in Norway. The recommendations are based on landslide types and the terrain in the downhill side as shown in Figure 2. The recommendations are for estimating the retrogression distance (L_u) of onshore landslides in sensitive clay deposits and are given in equation (3) to (5).

Flow slide in channelized terrain:
$$L_u = 3.0\ L \quad (3)$$

Flow slide in open terrain:
$$L_u = 1.5\ L \quad (4)$$

Flakes or rotational landslides:
$$L_u = 0.5\ L \quad (5)$$

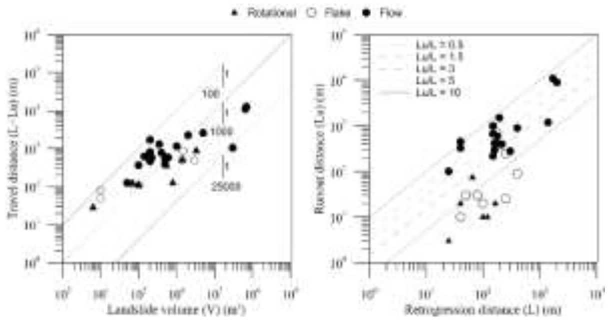

Figure 2. Relationships between travel distance ($L+L_u$) and landslide volume (left) and runout distance (L_u) and retrogression distance (L) (right) for landslides in Norwegian sensitive clays (Strand et al. 2017).

An attractive aspect of the empirical relationships given in equation (1) – (5) is their simplicity. The only required input data are landslide volume, the average width of landslide pit and retrogression distance. In contrast, empirical relationships are often established using large datasets of observed debris flows without considering the specific characteristics of the sliding debris or topographical aspects that may influence the dynamic behavior and trajectory (Strand et al. 2017). This calls for further insight into the post failure movements of landslides.

3 ENERGY INNVOLVED DURING LANDSLIDE MOBILITY

The importance of understanding flow slides using energy absorbed in shearing of intact material was first addressed in 1967 by Bishop and has continued to be a subject of study by several researchers in investigating flow slides on sensitive clays (e.g. Tavenas et al. 1983, D'Elia et al. 1988; Leroueil et al. 1996; Locat 2008; Quinn et al., 2011, Thakur and Degago 2013; Thakur et al. 2014). The energies involved in a landslide is explained in a simplified manner here below.

During a sensitive clay slide, the initial potential energy (E^P) is transformed partly into the energy consumed in the disintegrating of the soil to its remolding state (E^R) and in the slide movement (kinetic and frictional energy, E^{KF});

$$E^P = E^R + E^{KF} \quad (6)$$

This implies that the available potential energy to be transformed (E^P) and the required remolding energy (E^R) have huge significance in deciding the extent of landslides in sensitive clays. As suggested by Eqn. 6 also, for a given change in E^P, sensitive clays with higher E^R result in smaller slide movement (because of lesser E^{KF}) than sensitive clays with lower E^R. The slide movement is characterized by the runout distance and the retrogression distance, which is controlled by the amount of energy transferred to E^{KF} during the slide process.

4 REMOLDING ENERGY

Remolding energy (E^R) is the strain energy involved in remolding of a material. Considering clays that display elastic hardening followed by a strain-softening behavior, the shear stress (τ)-shear strain (γ) response can schematically be idealized as in Figure 3. The subscripts p and r represent the peak and the residual states, respectively. The area (B) under the τ - γ curve after the peak undrained shear strength (c_{up}) represents the second-order work during the remolding process.

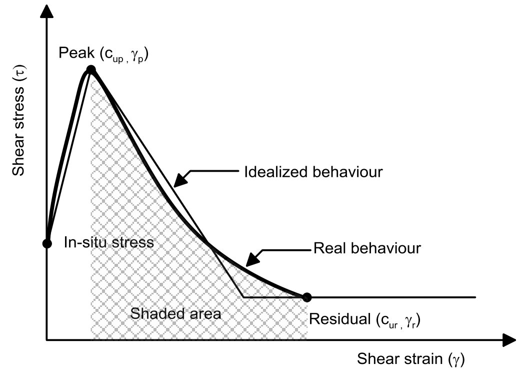

Figure 3. Illustration of the remolding energy concept using an idealized stress-strain behavior of sensitive clay.

4.1 *Analytical solution*

For an ideal behavior of sensitive clays (Fig. 2), the total remolding energy (area B) can be defined as;

$$E^R = c_{ur}(\gamma_r - \gamma_p) + \frac{1}{2}(c_{up} - c_{ur})(\gamma_r - \gamma_p) \quad (7)$$

Normally $c_{ur} << c_{up}$ for sensitive clays and considering a n index $n = \gamma_r/\gamma_p$ that gives a measure of sensitivity in terms of strain, Eqn. 7 can be approximated to

$$E^R \sim \frac{(n-1)}{2} c_{up} \cdot \gamma_p \quad (8)$$

Higher n indicates that larger E^R is required to disintegrate a material. In Equation 8, E^R is approximated by less than 5 % for sensitive clays having sensitivities between 50-1000. Majority of sensitive clays responsible for landslides have a sensitivity over 100 and less than 1000. Therefore, equation 8 shall be considered a reasonable approximation. Undrained shear strength (cup) is a function of pre-consolidation pressure (p_c') such that it can be related as $c_{up}=\alpha.p_c'$. In other words, E^R is directly related to the pre-consolidation pressure, the strain softening index n and strain at fully disintegration state γ_p. Ironically, as often anticipated the single parameter sensitivity S_t is not sufficient to fully describe the remoldability of sensitive clays.

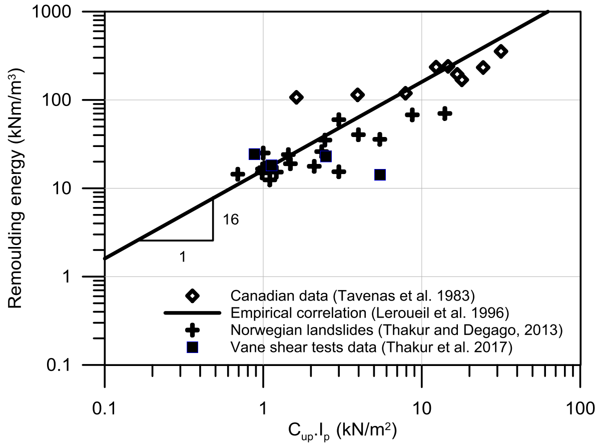

Figure 4. Remolding energy for various clays.

4 .2 *Determination of remolding energy*

Determination of remolding energy is not a straightforward task. However, Tavenas et al. (1983) did some pioneering work to estimate the disintegration energy of seven different Canadian sensitive clays using different laboratory set-ups. They attempted to simulate different processes by which a sensitive clay may be disintegrated during a landslide event. Accordingly, these processes are the shearing along with continuous straining and displacement along a failure surface, squeezing and extrusion between relatively intact clay blocks, impact of clay block on the bottom of the slide bowl or impact on clay blocks from falling objects or soil. Tavenas et al. (1983) reproduced these processes in the laboratory using some special arrangements. For the tested Canadian clays, the remolding energy (E^R) varied between 125 kNm/m^3 to 600 kNm/m^3. Based on the laboratory data, Leroueil et al. (1996) proposed an analytical equation (Eqn. 9) to estimate remolding energy;

$$E^R = 16. \ c_{up}. \ I_p \quad (9)$$

Locat et al. (2008) have validated this equation using da ta from 22 landslides in Canadian sensitive clays. Recently, Thakur et al. (2015) made an effort to determine remolding energy of Norwegian sensitive clays using a field vane shear apparatus. Despite the limitation (installation effect, partial drainage, progressive failure in sensitive clays, local pore water pressure drainage and strain rate) related to the vane shear tests, the obtained results were satisfactory and valuable; most importantly promising for further research. Following this approach, remolding energy determined for Finnish clay as well and results are presented in Thakur et al. (2017). The measured remolding energy was between 10-40 kNm/m^3, which is much lower than what is suggested for the Canadian sensitive clays. The difference is attributed to the fact that the tests were carried out for soft Norwegian and Finnish clays whereas the Canadian clays were mostly over-consolidated. Despite these differences, as shown in Figure 4, Equation 9 seems to be in good agreement with the Canadian as well as Norwegian and Finnish clay.

5 REMOLDING ENERGY VS POST FAILURE MOVEMENTS

The major interest of this study is to investigate the role played by the E^R in deciding the post-failure movements' i.e. Retrogression distance (L) and runout distance (L_u). These movements depend on several factors including the thickness of the dry crust and sensitive clay layers, boundary conditions, and topographical aspects, which may allow sensitive clays to "escape" from the slide scarp. (Thakur et al. 2014). However, for sake of simplicity a preliminary study is performed using the data from 33 Norwegian landslides presented by Thakur et al. (2014). The geotechnical and geomorphological data can be obtained from Thakur et al. (2014). The potential energy (E^P) per unit volume was simply calculated in relation to initial geometry. The potential energy per unit volume was calculated using $2\rho gH/3$. Here ρ is the mass density of sensitive clay, H is the slope height and g is the gravitational acceleration. The remolding energy (E^R) was calculated using Equation 9. Remolding energy ratio was correlated with post-failure movements. The remolding energy ratio is defined as a ratio between E^R and the maximum available potential energy. The remolding energy ratio indicates how large amount of potential energy will be consumed in the remolding o f sensitive clays. The analysis indicated that as low as only 5 % of total potential energy would have been sufficient to remold Norwegian sensitive clays and the remaining energy would have been left for the possible movement of the sensitive clay debris. The fact that the lower remolding energy ratio was obtained for the Norwegian sensitive clays subjected to large runout. However, a well-defined trend between remolding energy ratio and L and L_u was not found for the 33 Norwegian landslides and this is mainly believed to be due to the various simplifications and landslide types involved in idealization. A better correlation, in the form of the trend lines may be found when identical landslide types are studied as previously suggested by Strand et al. (2017).

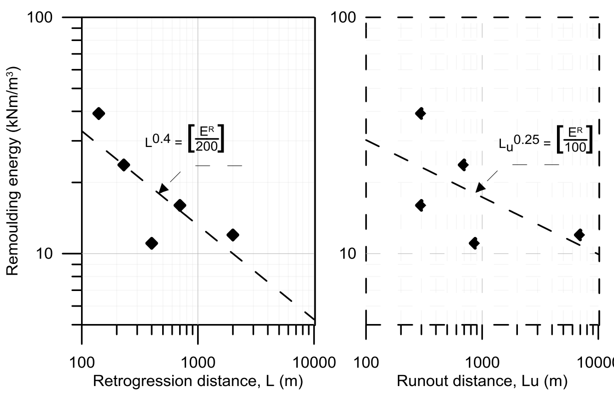

Figure 5. Remolding energy versus (a) run-out distance, (b) retrog ression distance for Norwegian flow slides in channelized terrain.

For this reason, five nearly similar Norwegian landslides were selected. These landslides are the Byneset landslide (2012), the Baastad landslide (1974), the Hekseberg landslide (1967), the Selnes landslide (1965) and the Verdalen landslide (1893). In these landslides, the nature of retrogression and the run-out process were similar and the slide debris had run-out along ravines. As shown in Figures 5 and 6, correlations for L and Lu is established and proposed. These correlations are valid for flow slide in channelized terrain only.

It is, therefore, the authors believe that taking into account topographical aspects, the nature of regression and run-out process could yield a better correlation among L, L_u and the remolding energy. The results presented in this study are a preliminary attempt to assess post-failure movements of landslides. However, to make this promising approach robust and practical further research is necessary.

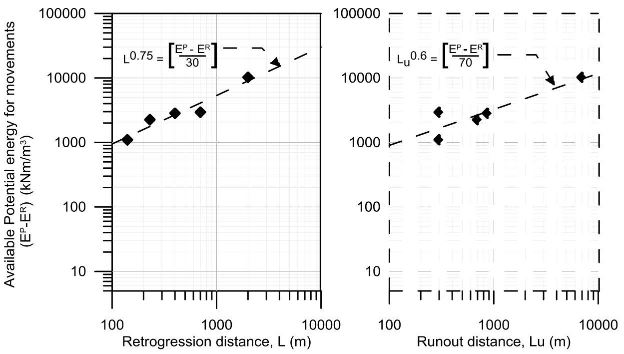

Figure 6. Available potential energy for movements versus (a) run -out distance, (b) retrogression distance for Norwegian flow slides in channelized terrain.

6 CONCLUSION

This paper attempts to demonstrate that required remolding energy is a useful aspect to consider while assessing the landslides in sensitive clays. Despite several simplifications, it was possible to show that the remolding energy is negatively correlated with the resulting retrogression and run-out distance. This observation from the landslide data supports earlier discussions that a greater run-out distance is associated with less use of energy for the remolding of sensitive clays, thereby making more energy available for the slide movement. The extent of post failure movements, among other factors, is dependent on secondary factors such as the topography and the stability of the area behind the initial slide zone. Still, an ability to remold and flow-out of the slide area will primarily decide the extent of retrogression.

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