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Run-out of Sensitive Clay Debris: Significance of the Flow Behavior of Sensitive Clays

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ABSTRACT: Geohazards in the form of massive flow slides in sensitive clay deposits have been responsible for the loss of human lives and damage to nearby infrastructure. The run-out of sensitive clay debris involved in such flow slides is, among others, largely influenced by the remolded shear strength (c_{ur}) of the sensitive clays. The present work studied this factor using a small-scale model referred to as the run-out test. The results demonstrated that sensitive clay debris with c_{ur} < 0.3 kPa have a potential for a longer run-out, whereas a very short run-out was observed for the sensitive clay debris with c_{ur} >1 kPa. These observations were back-calculated using the three-dimensional numerical tool DAN3D.

1. INTRODUCTION

Rapidly developing flow slides in sensitive clay deposits possess substantial destructive capabilities, resulting in the loss of life and destruction of surrounding properties. In the last 40 years, there have been one or two sensitive clay landslides per decade with volumes exceeding 500,000 m^3. In Norway alone, several hundred people have died in such landslides in sensitive soft clay slopes, and as recently as 1893, the Verdal landslide killed 116 people (Furseth, 2006; Walberg 1993; Issler et al. 2012; Oset et al. 2014). Geotechnical assessments of such flow slides include an estimation of the retrogression and prediction of the run-out of the slide debris. Although the estimation of landslide retrogression in sensitive clays has received considerable attention (*e.g.,* Lebuis and Rissmann 1979; Tavenas et al. 1983; Karlsrud et al. 1985; Trak and Laccasse 1996; Leroueil et al. 1996; Vaunat and Leroueil 2002; Thakur and Degago 2012), an appropriate method for investigating the run-out of sensitive clay debris remains the focus on ongoing research (*e.g.,* Mitchell and Markell 1974; Karlsrud 1979; Edger and Karlsrud 1982; Norem et al. 1990; Trak and Lacasse 1996; Locat and Leroueil 1997; Hutchinson 2002; Vaunat and Leroueil 2002; Hungr 2005; Locat and Lee 2005; Khaldoun et al. 2009; L'Heureux 2012; Issler et al. 2012; Thakur et al. 2013 & 2014).

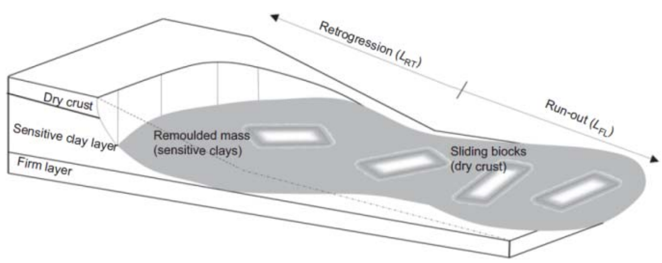

Figure 1 Flow slides in sensitive clays (Thakur and Degago, 2013)

The run-out of sensitive clay debris is dependent on several factors, including the thickness of the dry crust, sensitive clay layers, boundary conditions, and topographical aspects that may allow sensitive clays to 'escape' from the slide scarp (Mitchell & Markell 1974; Lebuis and Rissmann 1979; Tavenas et al.1983; Karlsrud et al. 1985; L'Heureux 2012; Thakur et al. 2012, 2013 & 2014). However, the ability of the clay debris to disintegrate and thus flow is one of the decisive factors in determining the run-out. Recent studies by Thakur et al. (2012), Thakur and Degago (2012), and Thakur et al. (2013 & 2014) have shown that seemingly small variations in the remolded shear strength (c_{ur}) have significant effects on the flow behavior of sensitive clays. Based on these studies, this paper presents work aimed at experimentally and numerically describing how the flow behavior influences the run-out distances of sensitive clay debris under given topographical settings. This study further investigates whether all sensitive clay debris has the same potential for run-out.

2. BACKGROUND

Highly 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. Rosenqvist (1953) demonstrated that the sensitivity of Norwegian marine clays is related to the leaching of salts by fresh groundwater within the grain structure. 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.

Transformation from an intact material to a fully remolded state at their natural water content is a typical characteristic of highly sensitive clays (Figure 2). Such peculiar behavior is mainly responsible for the large run-out of the debris involved in flow slides in sensitive clays. To understand this aspect, a brief review of literature on the prediction of run-out distances and the characteristics of sensitive clays in their intact and remolded states is presented here.

Figure 2 Images of a sensitive clay sample in intact (left) and fully remolded states (right)

2.1 Review of run-out calculation methods

Over the years, many different run-out and intensity calculation methods have been developed to perform debris-flow hazard assessments (*e.g.,* Dai et al. 2002; Hungr et al. 2005; Rickenmann 2005). The methods available for run-out estimation can be divided into four different classes: empirical, analytical, simple flow routing, and numerical.

Empirical relationships are the most commonly adopted techniques for estimating the run-out distance of slide debris. Among others; Mitchell and Markell (1974), Hsü (1975), Karlsrud (1979), Edger and Karlsrud (1982), Karlsrud et al. (1985), Cannon (1993), Corominas (1996), Locat and Leroueil (1997), Rickenmann (1999), Fell et al. (2000), Fannin and Wise (2001), Legros (2002), Hutchinson (2002), Vaunat and Leroueil (2002), Bathurst et al. (2003), Crosta et al. (2003), Hungr (2005), Locat and Lee (2005), L'Heuruex(2012), and Thakur and Degago (2013& 2014) have reported empirical correlations for estimating the run-out distance for various geomaterials, including sensitive clays.

Ricknemann (1999) proposed an expression (Equation. 1) based on a worldwide dataset including 154 debrisflow events. This function suggests that the maximum run-out distance (L_{FL}) is mainly linked with the vertical drop (H) and the debris-flow volume (V) (Figure 3).

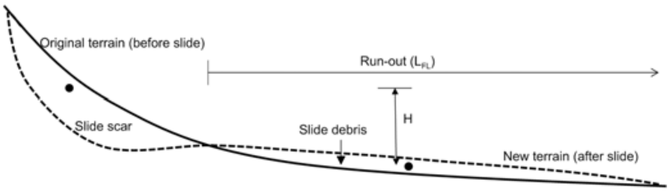

Figure 3 The idealized run-out of the debris from a slide event

$$L_{FL} = 1.9\ V^{0.16}\ H^{0.83} \tag{1}$$

Corominas (1996) compared a dataset of 52 debris flows, debris slides, and debris avalanches that occurred in the Pyrenees to 19 worldwide events and proposed the following relationship:

$$L_{FL} = 1.03\ V^{-0.105}\ H \tag{2}$$

Locat et al. (2008) proposed a correlation between the run-out distance and normalized slide volume for Canadian sensitive clays based on collected landslide data. A unique empirical relation could not be derived due to scatter in the data; instead, upper and lower limits were suggested. The upper limit is given as follows:

$$L_{FL} = 1.9\left(\frac{V}{W_{avg}}\right)^{0.78} \tag{3}$$

Similarly, L'Heureuxet al. (2012) suggested the following relationship for Norwegian sensitive clays:

$$L_{FL} = 9\left(\frac{V}{W_{avg}}\right)^{0.78} \tag{4}$$

Equations 3 and 4 suggest that the run-out distance for sensitive clays generally increases with an increasing volume of the slide debris (V) per unit width (W_{avg}).

Another important relationship that has been noted is that the run-out distance in sensitive clays is closely related to the retrogression distance (L_R). Locat et al. (2008) suggested a maximum run-out distance for Canadian landslides as:

$$L_{FL} = 8.8\ L_R^{0.8} \tag{5}$$

L'Hueruexet al.(2012) suggested a maximum run-out distance for Norwegian landslide as:

$$L_{FL} = 9\ L_R \tag{6}$$

The major advantage of these empirical relationships is their simplicity. The only required input data are the longitudinal profile of the flow path and the landslide volume. 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.

The limitations of the empirical approach are often compensated for using analytical models. Analytical approaches have been developed for rock avalanches *e.g.,* Körner 1976; Hungr et al. 2005, flow slides *e.g.,* Hutchinson1986, snow avalanches *e.g.,* Voellmy 1955; Perla et al. 1980, and debris flows *e.g.,* Rickenmann 1990.

Sassa (1988) proposed an analytical model so called the friction or sled model. The landslide is represented by a mass concentrated at one point, and the total vertical drop and the total horizontal travel distance of the mass are respectively noted H and L. The sliding resistance T obeys the law:

$$T = \mu N \tag{7}$$

where μ is the friction coefficient, N is the normal force exerted by the mass on the sliding surface. The loss of potential energy to the energy dissipated by friction was considered to be equal. Accordingly:

$$H/L = T/N = \mu \tag{8}$$

μ is usually consider to be equal to the tangent of the friction angle φ of the material. Scheidegger (1973) proposed to estimate the run-out distance of rock falls:

$$L_{FL} = L_T\ (1 - H_T\ L_T^{-1}) tan\varphi_m \tag{9}$$

Here, the reach angle (φ_m) is expressed by arctan (H_T /L_T). H_T and L_T are respectively the vertical and horizontal distances from the head of the landslide source to the distal margin of the displaced mass.

An approach based on the energy balance is suggested by *e.g.,* Scheidegger 1973; Hsü1975; Sassa 1988; Vanaut and Leroueil 2002; Thakur and Degago 2013 for the estimation of run-out in sensitive clay debris. The approach by Thakur and Degago (2013) suggests, in flow slides of sensitive clays, the change in potential energy before and after the slide is transformed to a different form of energy that results in disintegration of the soil to its remolding state and slide movement (kinetic and frictional energy). The available potential energy is a function of slope geometry and soil density. The available potential energy to be transformed and the disintegration energy have huge significance in deciding the extent of landslides in sensitive clays. It also implies that, for a given change in potential energy, sensitive clays with higher disintegration energy result in smaller slide movement than sensitive clays with lower disintegration energy. The slide movement is characterized by the run-out distance and the retrogression distance, which is controlled by the amount of energy transferred to kinetic and frictional energy during the slide process.

Over the past two decades, a large number of numerical models have been developed for other landslide types or snow avalanches. Although the constitutive behavior of slide debris remains an open topic for discussion, quasi-two-dimensional numerical models (e.g., BING (Imran et al. 2001) and NIS (Norem et al. 1987, 1989)) and quasi-three-dimensional models (e.g., DAN3D (McDougall and Hungr, 2004; McDougall, 2006), MassMov2D (Beguería et al., 2009), LS-RAIPD (Sassa, 1988; Sassa 2004; Sassa et al. 2010) and RAMMS (Christen et al. 2002)) are commonly used to estimate run-out distances. Importantly, none of these tools were developed for the estimation of the run-out distance of sensitive clay debris flows.

2.2 Characterization of sensitive clays

A characterization of sensitive clays is presented in Figures 4, 5 and 6 using the index properties obtained for more than 500 samples taken from 130 boreholes throughout Norway.

Norwegian sensitive clays follow the A-line, PI = 0.73 (LL - 20), on Casagrande's plasticity chart (Figure 4). Here, PI and LL refer to the plasticity index and liquidity limit, respectively. Norwegian sensitive clays having S_t> 15 are typically low-plasticity materials, with plasticity index (I_P) ≤ 10% , meaning that they can be subjected to fully remolding even at a very little deformation.

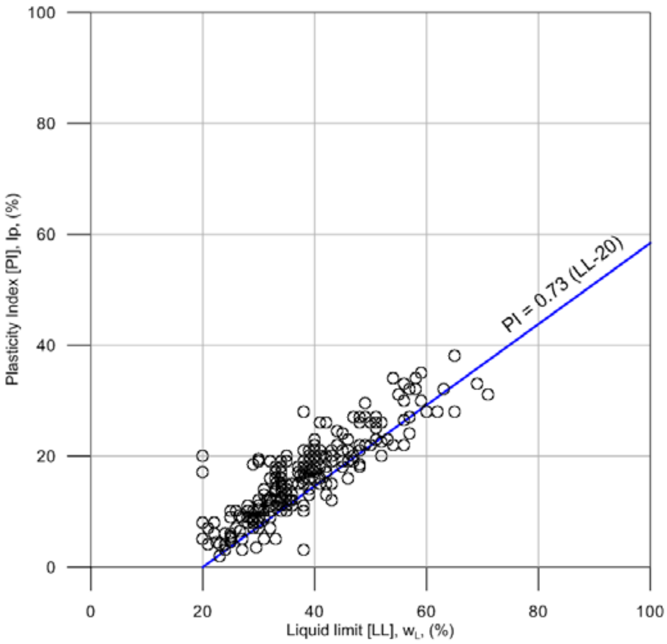

Figure 4 Norwegian sensitive clays plotted on Casagrande's plasticity chart

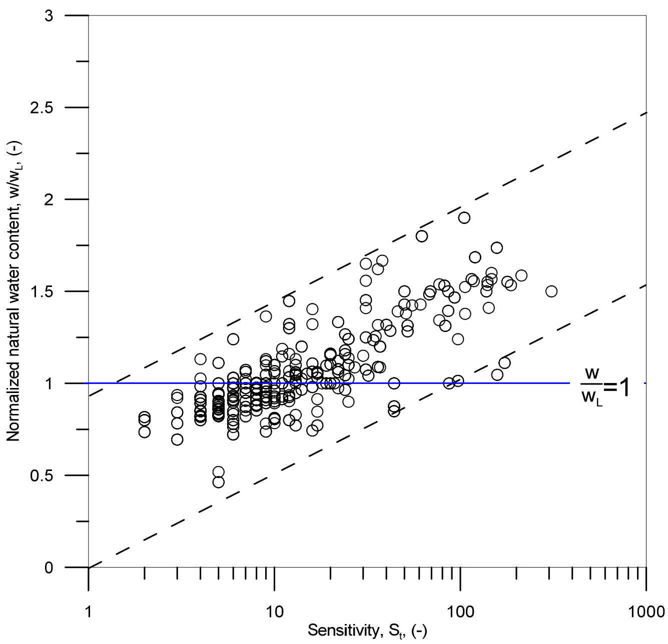

Figure 5 The relationship between soil sensitivity and the normalized natural water content for Norwegian sensitive clays

Sensitive clays are uniquely related to their S_t and LL (w_L) values, and the majority of highly sensitive clays have a water content (w)>w_L (Figure 5). A ratio w/w_L> 1.0 characterizes open void structures that allow sensitive clays to be met a stable in nature. Such clays are susceptible to flow slides when their liquidity index (I_L) is greater than 1.2 (e.g., Lebuis and Rissmann 1979; Leroueil et al. 1983; Burland 1990; Thakur et al. 2014). The friction angle φ varies between 25°and 28° when these clays are normally consolidated, although φ decreases with increasing w/w_L, as shown in Figure 6.

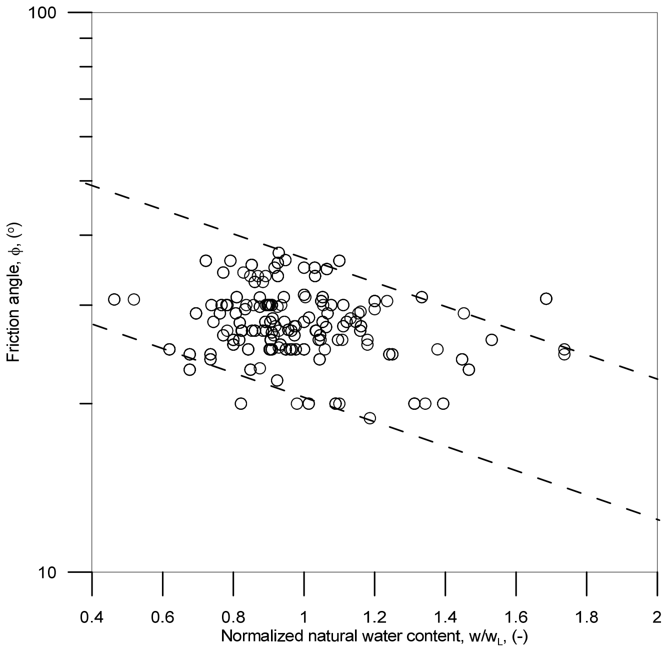

Figure 6 The relationship between the friction angle measured from consolidated triaxial tests under the undrained condition and the normalized natural water content for Norwegian sensitive clays

Literature suggests (*e.g.,* Lacasse et al., 1985; Lunne et al. 1997) that routine sampling procedures (e.g., using 54-mm cylinders) lead to sample disturbances in sensitive soft clays. In turn, sample disturbances lead to, among other problems, the under estimation of the pre-consolidation pressure, c_{ui} and the rate of strain softening. Figure 7 illustrates the effect of sample disturbance in asoft sensitive clay from the Kløfta roadway project in Norway. The figure shows that a 54-mm sampler induced a large amount of disturbance in the sample. Consequently, the stress-strain-deformation characteristics obtained from laboratory tests are not representative of the true response of the material in the field. Therefore, larger-diameter samplers, such as 76-, 95-, or 250-mm samplers, are becoming increasingly popular in Norway. In addition, the sample quality also influences S_t. Table 1 presents a comparison between the measured c_{ui} and $S_t$values from a block sample and from 54-mm diameter samplers from the Kløfta roadway project in Norway. The measured value of c_{ur} = 0.2 kPa was clearly unaffected by the type of sampling. The measured c_{ui} for a block sample was 27 kPa, whereas 54-mm-diameter samples at the same depth had c_{ui} values of 8.6 and 11.7 kPa. The range of error for the S_t values in Table 1 was on the order of 300%, which has a significant effect in the interpretation and design procedures. Consequently, c_{ui} and S_t are influenced by sample disturbance, whereas c_{ur} is not dependent on the quality of the sample.

Table 1 The effects of sample disturbance

Depth [m]	**c_{ui} [kPa]**	**c_{ur} [kPa]**	**S_t [-]**
18.5[A]	27	0.2	135
18.5[B]	8.6	0.2	42
18.5[B]	11.7	0.2	58

[A] *Block sample;* [B] *54-mm-diameter sample*

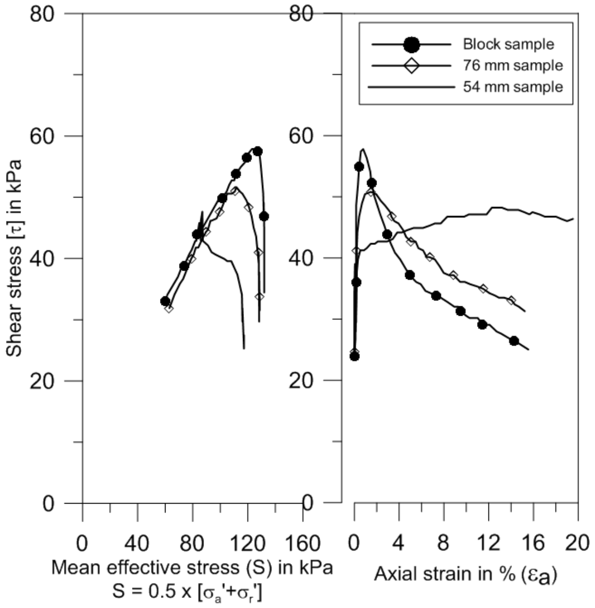

Figure 7 The effects of sample disturbance illustrated using anis tropically consolidated undrained triaxial tests on soft sensitive clays sampled using different samplers. Here, σ_a' and σ_r' are the effective stresses in the axial and radial directions, respectively. The presented results are from a Kløfta roadway project in Norway. (Source; SVV, 2009)

During a landslide, the flow behavior of slide debris can be quite complex and various types of behavior can exist depending on natural water content, salt content, and liquidity index of the soil (Locat and Demers, 1988). Locat and Demers, (1988) and Locat and Lee (2005) suggests that the study of the plastic viscosity, yield stress, remolded strength, and their correlations provides a good understanding of the flow characteristics of slide debris. They have presented the rheological properties of Canadian sensitive soils. Such studies are yet to done for Norwegian sensitive clays. The literature reports a large discrepancy between laboratory and back-calculated field values of viscosity and the measured shear stress. As the objective of this paper is to discuss the correlation of the flow potential of sensitive clay debris and their remolded shear strengths, no further discussion is presented with regard to rheological models and their applicability to run-out distance modeling.

3. LABORATORY MODEL TEST

In this section, a simple test procedure used to estimate run-out distances is presented. The model test aims to provide the basis for understanding of the run-out of fully remolded sensitive clay debris using a small-scale laboratory model. Thakur and Degago (2012) have presented a similar test, the quickness test, to define the collapse behavior of remolded sensitive clays. However, the quickness test is not meant to model the run-out.

3.1 Test procedure

The model test is based on the concept of a dam breach. The model test is performed by filling a box with remolded sensitive clay, slowly releasing the filled mass from one end (gate), and measuring the run-out distance (L_{FL}) as the material is subjected to flow. The open-ended box used in this study has alength (L_o) = 200 mm, height (H_o) = 150 mm, and width (Wo) = 100 mm. An overview of the model used in the study is presented in Figure 8. The thoroughly remolded material is placed into the box and leveled off and then allowed to flow outward as the gate is slowly lifted upward with minimum disturbance to the sample. The flow length or the run-out (L_{FL}) is observed and measured along a gently inclined ramp. An inclination of 8.5° was chosen.

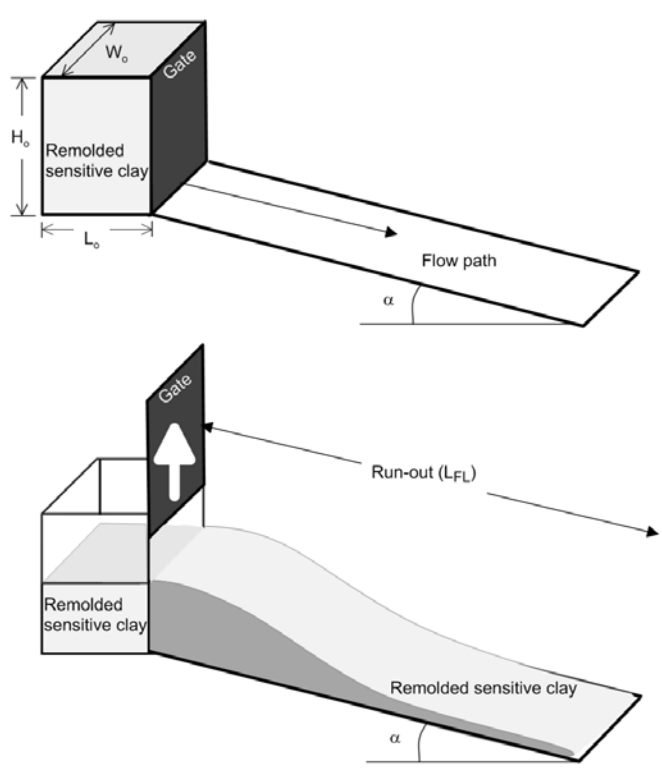

Figure 8 The run-out model test set-up

3.2 Characterization of the tested materials

The model tests were performed on sensitive clay samples collected from three different landslide locations in central Norway. These sites have been studied extensively in connection with landslide hazards. The laboratory index properties of the sampled material are presented in Table 2. The liquid limit (w_L), c_{ui} and c_{ur} of the tested material were obtained using the fall-cone method, as described by the National Standard NS 8015 in Norway.The remolded shear strength (c_{ur}) of sensitive clays are dependent on the natural water content, which is illustrated in Figure 9 for all three clays. The tested sensitive clays had different salt contents, clay fractions, and mineral compositions, which in turn led to the same c_{ur} values at different water contents (w).

Table 2 Engineering characterization of the tested material

Properties	Byneset	Lersbekken	Olsøy
Sampling depth (H) [m]	4 – 12	6 – 10	4 – 15
Clay fractions (< 2 μm) [%]	30 – 55	30	50 – 65
Water content (w) [%]	27 – 48	22 – 34	28 – 38
Plasticity index (I_P) [%]	3 – 15	5 – 7	3 – 10
Liquidity index (I_L) [-]	0.9 – 5.4	0.7 – 2.0	0.6 – 3
Undisturbed undrained shear strength (c_{ui}) [kPa]	5.2 – 72	12 – 58	60 – 100
Remolded undrained shear strength (c_{ur}) [kPa]	0 – 3	0 – 2	0 – 2.1
Sensitivity (S_t) [-]	4 – 400	16 – 29	30 – 100
Over consolidation ratio (OCR) [-]	1.1 – 3.3	1.8 – 2.0	2– 4
Salinity (g/l)	0.6 – 0.74	1.5 – 1.6	0.9– 2.0

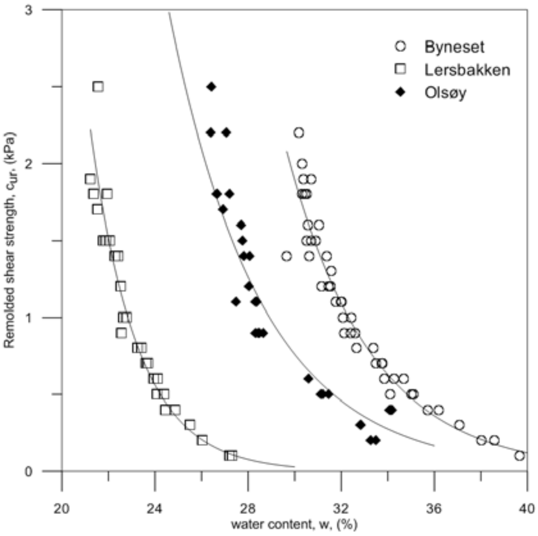

Figure 9 The remolded shear strength as a function of the natural water content for the tested sensitive clays.

3.3 Results and observations

Run-out model tests were performed on more than 35 different remolded sensitive clay samples extracted from the Lersbekken, Byneset, and Olsøy landslide locations. The observations during a run-out test conducted on Byneset, Lersbekkenand Olsøy clay indicated that sensitive clays with c_{ur}= 0.1 kPa behaved as fluids, and therefore, the highest run-outs were observed for this particular c_{ur}. Importantly, the lowest possible c_{ur} value that can be measured using the fall cone apparatus is 0.1 kPa. Sensitive clays having c_{ur} = 0.1 kPa behave like water, and therefore, the run-out in such materials will depend on the available slide volume (remolded sensitive clay debris) and the formation of the terrain. Because the aim at this stage of the study was to visualize the run-out of sensitive clays at different c_{ur} values but not to predict the run-out distance for c_{ur} = 0.1kPa, the run-out (L_{FL}) at c_{ur} = 0.1 kPa was considered as a reference value for comparison with the run-outs observed at the other c_{ur} values. For this purpose, a normalized run-out, (L_F), which is the ratio of the flow length at a given c_{ur} to the run-out at c_{ur}= 0.1kPa, was used in this study. The relationship between L_F and c_{ur} is presented in Figures 10-12.

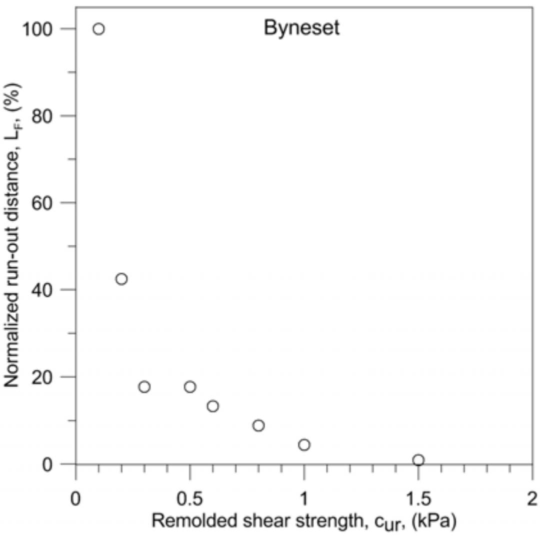

Figure 10 L_F versus c_{ur} values determined for soil samples collected from the Byneset landslide location

Interestingly, remolded sensitive clays having c_{ur} ~ 0.5 kPa are not as fluid as they were originally assumed, and sensitive clays with 0.5 kPa <c_{ur}< 2.0 kPa were semi solid in nature. This behavior can be observed in terms of L_F: L_F is reduced from 100% to approximately 18% for the Byneset clay, 22% for the Lersbakken clay, and 20% for the Olsøy clay when c_{ur} is increased from 0.1 to 0.3 kPa. L_F was further reduced by less than 95% when c_{ur} was increased to 1.0 kPa for all of the tested clays.

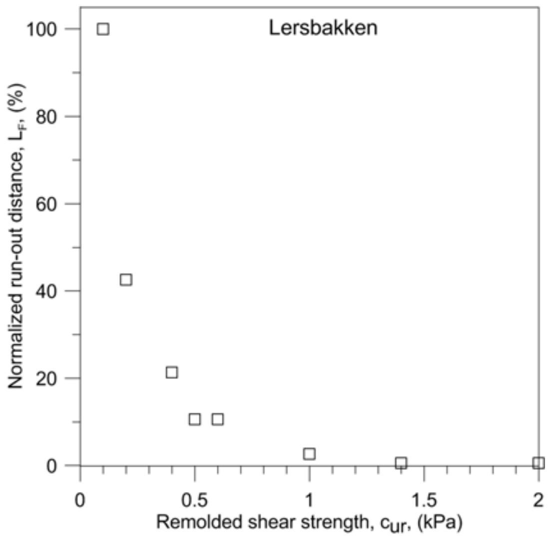

Figure 11 L_F versus c_{ur} values determined for soil samples collected from the Lersbakken landslide location

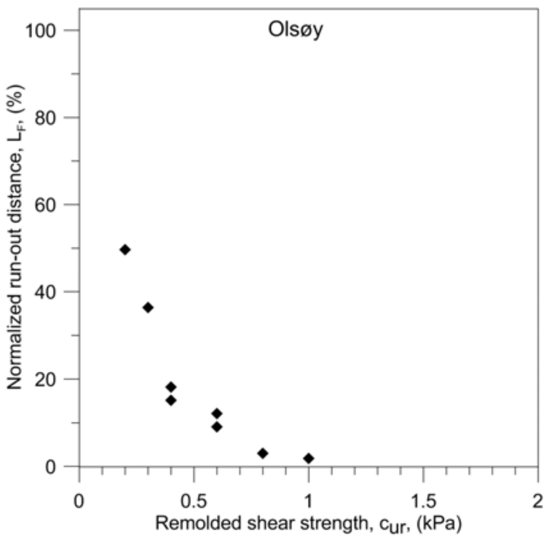

Figure 12 L_F versus c_{ur} values determined for soil samples collected from the Olsøy landslide location

The observed behavior is in line with Mitchell and Markell (1974); Lebuis and Rissmann(1979); Locat et al. (2008); Thakur et al. (2013& 2014) who reports that sensitive clays having c_{ur} > 1.0 kPa are less likely to experience a flow slide and therefore no run-out of the slide debris.

A combined plot with data for all three landslide locations is shown in Figure 13. For clay samples with c_{ur} > 1.0 kPa, very little run-out was measured. Interestingly, the run-out behavior of sensitive clay changed dramatically within the range c_{ur} < 0.3 kPa. The results of therun-out tests shown in Figure 16clearly demonstrate that the Lersbekken, Byneset, and Olsøy materials had nearly identical responses.

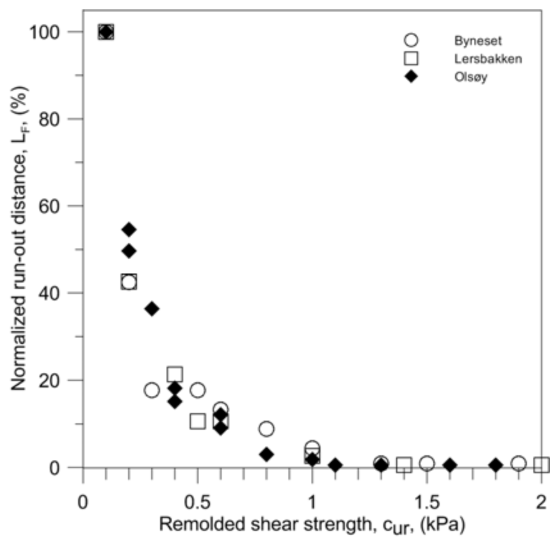

Figure 13 Compilation of L_F versus c_{ur} values registered on soil samples taken from the three landslide locations

4. BACK-CALCULATION OF THE MODEL TEST RESULTS USING DAN3D

As mentioned earlier, several numerical tools are available to simulate debris flow and flow slides in a variety of geomaterials, except sensitive clays. Issler et al. (2012) suggests that Dynamic Analysis of Landslides (DAN) in 3D can be an appropriate tool and has a great potential to model run-out in sensitive clays. Therefore, DAN3D was chosen in this workto study the effect of the c_{ur} value of sensitive clays on the run-out distance.

4.1 Brief description of DAN3D

Dynamic Analysis of Landslides (DAN) is a quasi-two-dimensional model that was developed by Hungr (1995) and was further extended to DAN3D by McDougall and Hungr (2004) and McDougall (2006). The version of DAN3D used in this study was kindly provided by Prof. Oldrich Hungr for use in research. The basic premise of the analysis is that as a result of sliding or other failure, a pre-defined volume of soil or rock ("the source volume") changes into a fluid and then flow downslope, following a path of a defined direction and width. A digital terrain model of the landslide path and a digital elevation model of the depth in the release area ("landslide scar") are prerequisite as the input. The run-out estimation can be performed using several alternative basal rheologies, including the frictional, the plastic, the Newtonian, the Bingham, and the Voellmy models:

Plastic model

$$\tau = \tau_y \tag{10}$$

Frictional model

$$\tau = (1 - ru)\, \sigma_n \tan \varphi \tag{11}$$

Newtonian model

$$\tau = 2\mu v/h \tag{12}$$

Bingham model

$$\tau = \tau_y + 2\mu v/h \tag{13}$$

Voellmy model

$$\tau = \sigma_n \tan \varphi + \gamma v^2/\xi \tag{14}$$

where τ is the bed shear stress, τ_y is the yield shear strength, *ru* is the pore pressure ratio, σ_n is the bed-normal total stress, φ is the apparent friction angle, γ is the unit weight of the slide debris, μ is the viscosity, v is the depth-averaged flow velocity, and ξ is the turbulent friction coefficient (in m/s^2). In general, there is a lack of knowledge about parameter like φ, μ, ξ and v for remolded Norwegian sensitive clay debris. Accordingly, the Newtonian model and the the Voellmy model or the Friction model could not be used in this study. Issler et al. (2012) suggests that the Bingham model is not suitable for sensitive clay debris. Therefore, despite its simplicity, the plastic model was chosen in this study.

4.2 Back-calculation of the model tests

Because all of the normalized run-out behaviors were nearly identical for all three clays, the model tests for the Byneset clay were chosen for the back-calculation. The back-calculation of the model tests in DAN3D require input files containing information regarding the topography and initial conditions (Figure 14) of the model tests in the form of three ASCII grid files. The calculations were performed using the plastic model (Equation 10) for various τ_y values. The τ_y was considered to be equal to c_{ur}. The input parameters were configured according to Table 2.

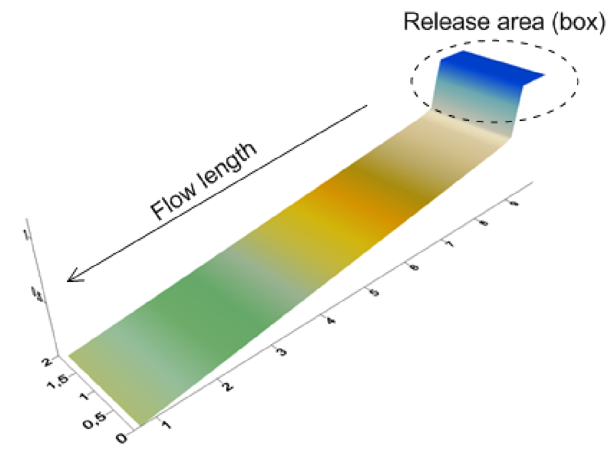

Figure 14 The path topography defined in the DAN3D calculations.

4.3 Simulation results and discussion

Thakur et al. (2013 & 2014) and Thakur and Degago (2012) reported that sensitive clays having $c_{ur} > 1.0$ kPa are less likely to experience a flow slide, i.e., zero retrogression after an initial slide and no run-out of the slide debris. This finding was confirmed by the model test results. Therefore, a back-calculation was performedat c_{ur} values up to 1.0 kPa. The numerically calculated run-out results for sensitive clay debris, in the form of a flow depth contour map for c_{ur} = 0.1, 0.3, and 1.0 kPa, are shown in Figure 15. The calculation results are in agreement with the model tests; i.e., lower c_{ur} values yield a higher L_{FL}. A comparison between the numerical calculation and the results from the model tests, presented in Figure 16, indicate an identical trend between the laboratory observations and numerical simulation. In particular, for c_{ur}<0.3 kPa, there was good agreement between the back-calculation using the plastic model and the laboratory test results. The run-out distance was drastically reduced with small increases in c_{ur}. Note that this particular range of c_{ur} is of interest because the majority of large flow slides in Norway *e.g.*, the landslides in Verdalin 1893, Braain 1928, Selnesin 1965, in Heksebergin 1967, in Baastad in 1974, in Rissain 1978, in Kattmarkain 2009, in Lyngenin 2010, and in Byneset in 2012 having L_{FL} > 200 m had $c_{ur} \leq 0.3$ kPa.

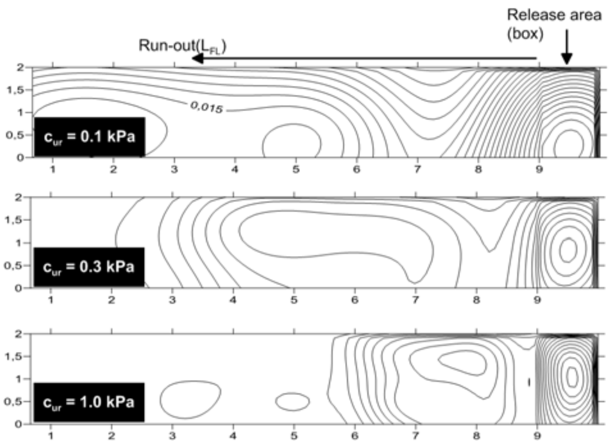

Figure 15 Run-out at various c_{ur} shown in a form of contour maps

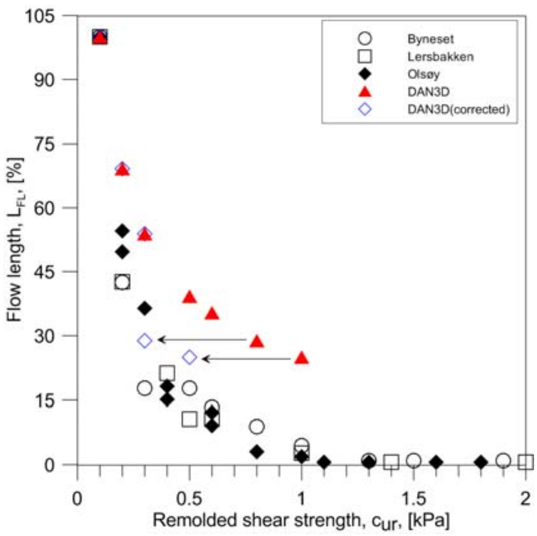

Figure 16 Back-calculated L_F for c_{ur} values for the Byneset sensitive clay along with the model test results

However, the numerical results appear to have over-predicted the flow length for sensitive clay debris having c_{ur} > 0.3 kPa. Such over-prediction is attributed to the choice of constitutive model. The plastic model in DAN3D assumes zero friction between the slide debris and sliding plane (or bed) along the flow path. In contrast, there will always be some degree offrictional resistance along the sliding plane in the model test, which will counteract the flow of sensitive clay debris. The amount of frictional resistance will depend on the roughness of the bed, slope of the sliding plane, thickness of the slide debris, and the internal friction of the material. In the case of sensitive clay debris having relatively low c_{ur} values, the friction resistance between the contact surfaces will be less important because the inter-particle friction between the sliding material will be sufficiently low (similar to that of water) that the contact friction will have little influence on the flow. In contrast, semisolid sensitive clays with larger c_{ur} values (>0.3 kPa) will flow similarly to a monolithic mass, and therefore, the friction at the contact plane will have a decisive role in the run-out process. For comparison purposes, a simple correction is applied to the numerical results. The correction (τ_y^*) is assumed to be equal to the shear stresses that may result on the sliding plane due to the weight of the slide debris itself. Accordingly, τ_y^* per m^2 can be expressed as $\gamma.H_o.sin\alpha$, where γ is assumed as 20 kN/m^3, H_o is 0.15 m, and α is 8.5°, resulting in an additional resistance of approximately 0.45 kPa. A new set of calculationsthat incorporate the additional τ_y^* were performed for sensitive clay debris having c_{ur} >0.3 kPa. The new results are presented in Figure 16 as DAN3D (corrected). Despite several approximations the new results exhibit a better fit with the results of the model tests. This simple exercise demonstrates the importance of considering the effect of bed friction in numerical calculations.

This simple back-calculation has encouraged the authors to study the run-out simulation for a complex case. Therefore, a back-calculation of a large flow slide, the Byneset landslide, occurred on the early morning of January 1, 2012 is presented in the next section.

5. BACK-CALCULATION OF THE BYNESET FLOW SLIDE

The Byneset flow slide took place in a highly sensitive clay deposit, and it is believed that the slide was initiated due to natural erosion at the toe of the slope. Byneset is located approximately 10 km west of Trondheim.The flow slide was approximately 150 m in width. The flow slide retrogressed backward to a distance approximately 450 m from the toe of the slope. The total run-out of the sensitive clay debris was approximately 870 m from the toe of the slope. The volume of the slide debris was estimated to be on the order of 3-3.5 × 10^5 m^3. A detailed ground investigation was performed by the authorities soon after the flow slide, and the results were presented by Thakur (2012).An overview of the geotechnical properties of the sensitive clay deposit from the flow slide area is presented in Table 2. Photos taken immediately after the flow slide illustrate that the slide masses evacuated the slide scar almost completely, as shown in Figures 17 and 18. The slide debris followed a water canal over a distance of approximately 870 m. Due to low discharge in the canal, water is not expected to have played an important role in the run-out of the slide debris.Completely remolded sensitive clay debris were observed along the entire flow path. A typical area of the flow is shown in Figure 19.

Figure 17 The Byneset flow slide (Source NVE, 2012). A closer view of the slide area and the gate

The Byneset flow slide was back-calculated using DAN3D. The remolded shear strengths of the sensitive clay involved in the flow slide were as low as 0.1 kPa. Accordingly, several simple approximations were made to back-calculate the flow slide:

(1) The slide debris obeys plastic basal rheology.

(2) The effects of bed friction along the contact surface between the flow path and slide debris were neglected.

(3) External factors, such as the effects of vegetation and water or snow along the flow path, were not considered in the model.

(4) It was assumed that the run-out is solely controlled by the remolded shear strength and topography of the area.

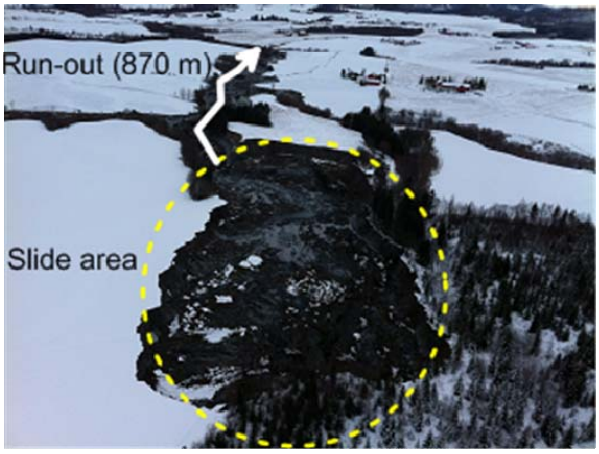

Figure 18 The extent of the Byneset flow slide (Source NVE, 2012)

Figure 19 The remolded sensitive clay debris along the flow path. (Source NVE, 2012)

The results at stages of 1%, 5%, 25%, 50%, and 100% (at the end) of the calculation are shown in Figure 20. The different stages of the simulation give an idea over how the slide debris must have run-away from the slide area along the canal. The total run-out of the slide debris obtained at the end of the simulation (100%) is quite similar to that observed in the field. To support this similarity, a topographical map of the area is shown in the same figure (lower left). The extent of the run-out of the sensitive clay debris on the map is marked as A, B, C, and D. the actual mapping and the calculated run-out distance using the plastic model are quite similar. The velocity of the slide debris was between 15 and 20 m/s, which is a relatively high velocity for such sub-aerial flow slides. It is difficult to verify the obtained velocity, as actual measurements are not available. However, slide debris involved in the Rissa landslide (1978) in Norway also had a velocity of approximately 11-12 m/s. Therefore, it is possible to conclude that the obtained velocity for the Byneset flow slide is reasonable. In summary, the back-calculated run-out distance is in agreement with the field evidences.

8. CLOSING REMARKS

This work presents a simple laboratory procedure that focuses on the effect of the remolded behavior of sensitive clays in terms of the run-out distance. Model tests were performed on more than 35 samples from three landslide sites. These results demonstrate that sensitive clays with $c_{ur} < 0.3$ kPa can be susceptible to large run-out, whereas the run-out is drastically reduced with increasing c_{ur}. This relationship was validated by back-calculating the model test and the Byneset flow slide using the DAN3D software. The numerical results demonstrated that the plastic model in DAN3D can be a good alternative for use with sensitive clays having $c_{ur} < 0.3$ kPa. However, the run-out distance can be over-estimated by the plastic model for sensitive clays having c_{ur} larger than 0.3 kPa in the absence of an appropriate correction with respect to the frictional resistance along the sliding surface. Further studies should be performed to test the other models in DAN3D using reliable input parameters. The model tests shall be carried on for different α values and using different volume of sensitive clay debris to study scale effects.

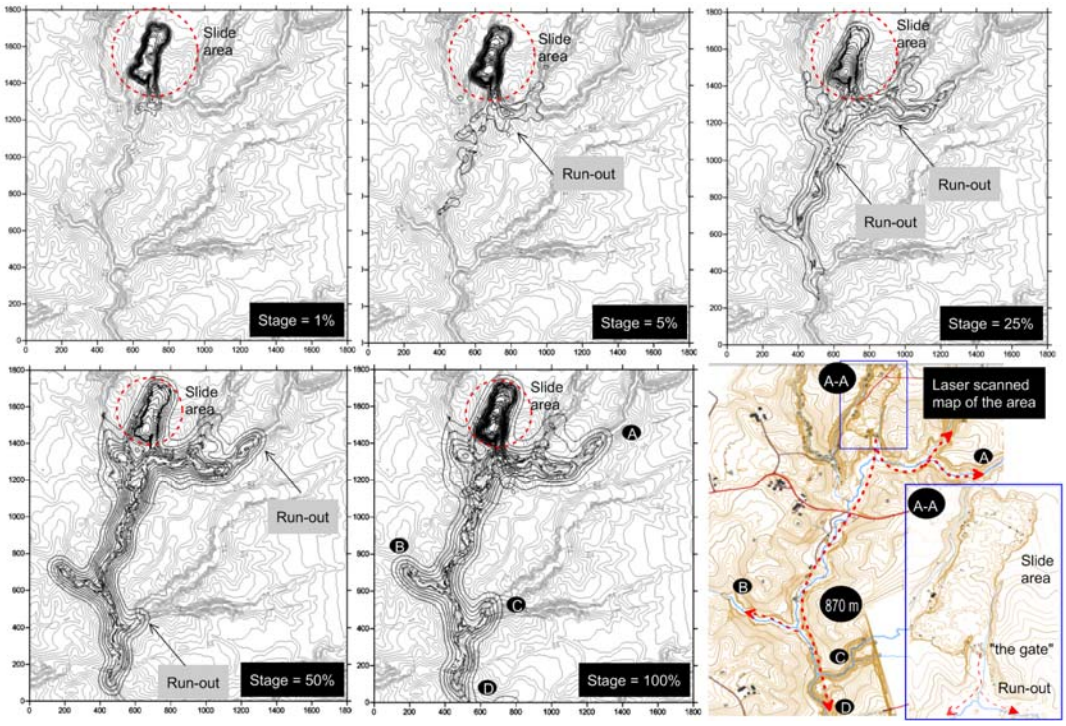

Figure 20 Back calculation of the Byneset flow slide. Run-out of sensitive clay debris, shown as a flow/deposit contour map at different stages of the simulation. The lower right figure shows the new topography of the area after the flow slide

9. ACKNOWLEDGEMENT

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