Quickness Test Approach for Assessment of Flow Slide Potentials

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ABSTRACT: Sensitive clays are known to result in massive flow slides and thereby resulting in loss of human lives and damaging nearby transportation infrastructures. Flow behaviors of these clays are usually characterized by their undrained shear strength at their fully remolded state. Therefore, assessment of flow slides in sensitive clays is directly related to their remolded shear strength. In other words, the extent of flow slides is crucially influenced by the remolded shear strength of the sensitive clays. However, a seemingly small variation in remolded shear strength has significant alteration in the flow behavior of sensitive clays. This paper study this aspect using a novel and pragmatic test procedure referred to as the quickness tests. This test amplifies the smaller range of remolded shear strength in term of parameter called quickness. The test has an advantage of giving a better visualization about the behavior of sensitive clays. Based on relevant Norwegian landslides data, a quickness based criteria to asses the potential for occurrence of flow slides is proposed.
Keywords: sensitive clays, landslides, flow slides, remolded shear strength, quickness

1. BACKGROUND

Transport infrastructures like roads and railways constitute part of major tools for accelerating economic, cultural and social development of societies. Transport infrastructures are normally spread over a large area and this requires systematic ground investigation scheme that can give reasonable characterization of soil. In areas characterized by sensitive clays, geotechnical investigation shall also aim at assessing potentials for flow slides. This requires detection of extent of the sensitive clays and assessment of any potential for flow slides. Such flow slides usually start with an initial slide of limited extent and are rapidly followed by a series of successive slides that develops into a large scale flow slide, see schematic representation in Figure 1.

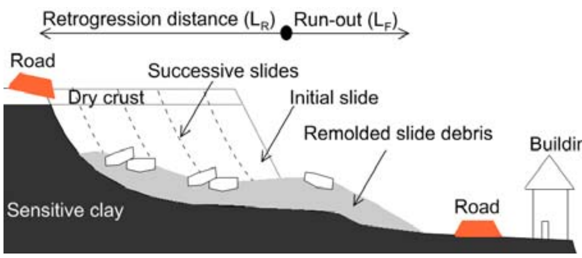

Figure 1 A sketch of retrogressive flow slide in sensitive clays. The retrogression distance (L_R) and the run-out distance (L_F) are measured from the toe of the slope

In the sensitive clay deposits of Scandinavia and eastern Canada, flow slides are particularly destructive, due to the possibility of small landslides initiating a flow slide, which may involve massive soil movements in the order of millions of cubic meters. Sensitive clays of Norway, when provoked by manmade or natural causes, have led to several landslide disasters throughout history (see e.g. Thakur et al. 2014). The most well-known are the landslides in Verdal and Rissa that lead to 116 and 1 causality, respectively, and huge resource destruction. These landslides have occurred in highly sensitive clays also known as quick clays. In the last 40 years there has been approximately 1 or 2 slides per decade with a volume exceeding 500 000 m^3. Since flow slides in sensitive clays possess huge destructive capabilities, there is a need for accurate assessment and prediction of flow slide potential in such materials. However, this is not a straightforward task due to the complexity associated with understanding of such materials (e.g. Bjerrum 1955; Meyerhof 1957; Bishop 1967; Lo and Lee 1973; Mitchell and Markell 1974; Tavenas et al. 1983; Karlsrud et al. 1985; Locat and Leroueil 1988, 1997; Bernander 2000; Fell et al. 2000; Leroueil 2001; Jostad and Andresen 2002; Vaunat and Leroueil 2002; Hungr 2005; Thakur 2007; Locat et al. 2008a & b, Locat et al. 2011, Quinn et al. 2011, Gylland et al. 2012, Thakur and Degago 2012; Jostad et al. 2014, Thakur et al. 2013& 2014, Oset et al. 2014**)**.

In Norway, more than 1750 highly sensitive clay deposits have been identified by the Norwegian authorities. However, there are parts of the country yet to be mapped. In the recent years, several new deposits of highly sensitive clays have been found during the ground investigation related to the transport infrastructures. Such unprecedented presence of sensitive clay deposits during the planning period usually result in delays and increase of project costs. Unfortunately, some projects are permanently postponed in absence of viable solutions and measures to counter the danger associated with the potential flow slides of sensitive clay slopes.

2. INTRODUCTION

Sensitive clay materials are found in several areas of the world including Alaska, Canada, Norway and Sweden. Sensitive clays are often categorized using term sensitivity (S_t) which is a ratio between the undrained shear strength (c_u) measured on the intact (c_{ui}) and the remolded (c_{ur}) sensitive clay using the fall cone method. Several classification systems have been proposed in the literature (Skempton and Northey 1952; Rosenqvist 1955; Norwegian Geotechnical Society (NGF) 1974) to define sensitive clays and a synthesis of these classifications is presented in Table 1. Rosenqvist (1953) showed that sensitivity of Norwegian marine clays is related to the leaching, by fresh groundwater, of the salts within the grain structure. Bjerrum (1955, 1961) show highly sensitive clays may have salt contents as lower than 0.5% while marine clays commonly have salt contents around 3 % or more.

Table 1 A summary of different sensitivity scales based on Skempton and Northey (1952), Rosenqvist (1955) and NGF (1974)

Sensitivity (S_t)	Classifications	Remarks
1	Non sensitive	*L*: low
1–8	*LS*	*M*: medium
8–16	*HS/ES/SK*	*H*: high
16–32 (30)	*K/MK*	*E*: extra
>32 (30)	*K*	*S*: sensitive
		K: quick

According to the current definition in Norway (NGF, 1974), a clay is said to be quick if it has a $c_{ur} \leq 0.5$ kPa. However, the Swedish Geotechnical Institute (SGI) defines quick clay as clay with $S_t \geq 50$ and a $c_{ur} \leq 0.4$ kPa (Rankka et al. 2004). It must be noted that quick clays are an extreme form of sensitive clays. In both cases, it has been stipulated that the remoulded material must behave as a viscous fluid rather than a plastic solid (Torrance, 1983). According to the current geotechnical code, issued by the Norwegian Water Resources and Energy Directorate (NVE), Norwegian brittle clays, that have an $S_t \geq 15$ and a $c_{ur} \leq 2.0$ kPa are treated as material susceptible to flow slides (NVE, 2010).

Sensitive clays are strain softening material characterized by a decrease in shear strength of the materials with increasing deformation once the peak shear strength is attained. These clays transform from their intact state to highly viscous fluid when subjected to a large deformation, see Figure 2. Standard triaxial tests give reliable results up to an axial strain level of 10 - 20%, and generally do not reveal the true residual strength of sensitive clays that requires very large strain. Ring shear tests, fall cone test or reversal shear box test are used to achieve a fully residual state. Given the simplicity, the remoulded shear strength of sensitive clays is often measured using the fall cone test. (e.g. Bjerrum and Kjærnsli 1957; Skempton 1964; Chandler 1966; La Gatta 1970; Bishop 1971, Eigenbrod 1972; Lupini et al. 1981; Lacasse et al. 1985; Bromhead and Dixon 1986; Burland 1990; Stark and Eid 1994; Stark and Contreas 1996; Burland et al. 1996; Bernander 2000; Leroueil 2001; Andresen and Jostad 2007; Mesri and Huvaj-Sarihan 2012).

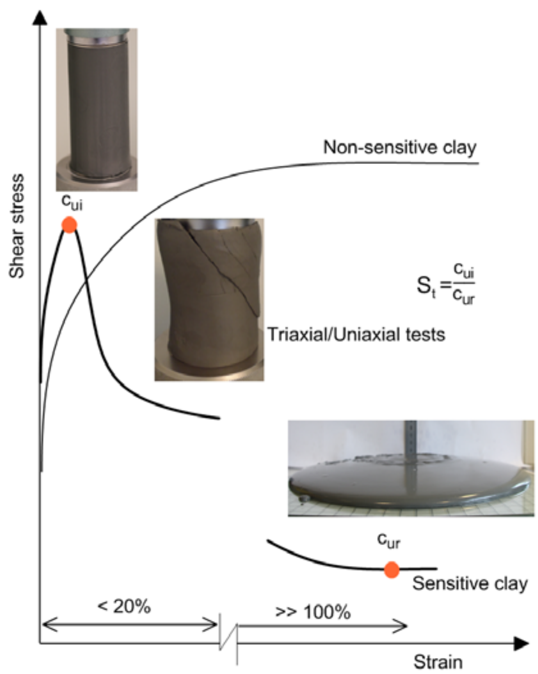

Figure 2 Schematic representations of a soft sensitive clay subjected to deformation; from the intact and the fully remolded state

Assessment of flow slides in geomaterials are complex because it demands, among others, (*i*) a complete understanding of the mechanical behavior of sensitive clays at its intact and remolded state (e.g. Rosenqvist 1955; Söderblom 1974; Lefebvre 1981; Tavenas and Leroueil, 1981; Flon 1982; Yong and Tang 1983; Lacasse et al. 1985; Janbu 1985; Karlsrud et al. 1985 and 1996; Berre 1986; Sandven and Sjursen 1998; Lunne and Lacasse 1999; Locat and Demers 1988; Leroueil et al. 1983 and 1996; Sandven et al. 2004; Lunne et al. 1997 and 2006; Larsen 2002; Berre et al. 2007; Long et al. 2009; Degago et al. 2011, Thakur et al 2012; Kornbrekke 2012; Thakur and Degago 2012, Thakur and Degago 2013; Thakur et al. 2013 & 2014) (*ii*) appropriate understanding of progressive failure and creep effects (e.g. Taylor 1937; Bjerrum 1955; Skempton 1964, 1970, 1977; Bishop 1967, 1971; Terzaghi and Peck 1967; Kenney 1967; Drury 1968; La Gatta 1970; Lo and Lee 1973; Vaughan and Walbancke 1973; Lefebvre 1981; Tavenas and Leroueil 1981; Aas 1981; Burland 1990; Viggiani et al. 1994; Leroueil et al. 1996; D'Elia et al. 1998; Bernander 2000; Fell et al. 2000; Hight et al. 2002; Jostad and Andresen 2002; Locat et al. 2003, 2008, 2011; Vermeer et al. 2004; Andresen and Jostad 2007; Quinn et al. 2011, Jostad et al. 2013) (*iii*) a knowledge about the realistic thickness of the localized shear failure zone (e.g. Jostad et al. 2006; Thakur 2007; Thakur 2011; Gylland et al. 2012), and (*iv*) a tool to assess for the debris flows that accounts for the peculiar behavior of sensitive clays (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 Leee 2005; L'Heureux 2012, Thakur et al. 2013). Given the complexity associated in assessing the potential for flow slides in sensitive clays, some of the issues can only be solved by additional research. By saying so, for practical purposes, one needs to simplify the problem and develop pragmatic approaches that can help in assessment of potential for flow slides and in adopting appropriate design approaches regarding construction on sensitive clay deposits. Accordingly, this paper further elaborates the novel and pragmatic approach, the quickness tests, proposed by Thakur and Degago (2012) to assess the potential for flow slides in sensitive clays collected at landslide locations. The quickness test has been performed for three different sensitive clays and the results are discussed in light of Norwegian landslide data.

3. FLOW SLIDE IN SOFT SENSITIVE CLAYS

Thakur et al. (2014) present an overview over 33 large Norwegian landslides in sensitive clay consisting of flow slides, rotational slides, flake and spreads type landslides in the Norwegian sensitive clays. Several factors such as; erosion along rivers or canals, and/or human activities have been responsible in triggering these landslides. For flow slides to occur after an initial slide, it is important that at least the following two criteria are fulfilled (Lebuis and Rissmann 1979; Tavenas et al. 1983, Karlsrud et al 1985; Trak and Laccasse 1996, Leroueil et al. 1996, Vanaut 2002, Thakur and Degago 2012):

1. The slide debris should be sufficiently remolded.
2. The slide debris should be able to flow out of the slide area if remolded.

There may be additional factors, such as the topography and the stability of the area behind the initial slide zone. However, if the two criteria mentioned above are not fulfilled, then vast landslides, such as those mentioned by Thakur et al. (2014) and those listed in Table 2, are unlikely to occur.

Table 2 Documented flow slides in Norwegian sensitive clays*

Year	Landslide^	L_R	L_F	V	c_{ur}	S_t	Nc
		[m]	[m]	[10^5 x m^3]	[kPa]	[-]	[-]
1625	Duedalen[1,2,3]	410	-	5	0.07	209	NA
1893	Verdal[4,5]	2000	5000	650	0.2	300	30
1928	Brå[2,5]	197	300	5	0.24	75	NA
1962	Skjelstadmarka[6]	600	2800	20	0.83	80	7
1965	Selnes[7]	230	400	1.4	0.35	100	6
1967	Hekseberg[8]	700	300	2	0.25	100	NA
1978	Rissa[9]	1200	600	55	0.25	100	8
1988	Balsfjord[10,11]	400	-	8	1.0	30	13
2009	Kattmarka[12]	300	350	3-5	0.24	63	8
2010	Lyngen[13]	153	411	2.5	0.14	51	11
2012	Byneset[14]	400	870	3.5	0.12	120	11

**L_R = Retrogression distance, L_F = run-out distance, V = slide volume c_{ur} = remolded shear strength, S_t= Sensitivity I_L= Liquidity index, NA = Not available*

^[1]Reite et al. (1999) [2]Trondheim Municipality reports, [3]Furseth (2006), [4]Natterøy (2011), [5]Holmsen (1929), [6]Janbu (2005), [7]Kenney (1967), [8]Drury (1968), [9]Gregersen (1981), [10] Rygg og Oset (1996), [11]Janbu (1991), [12]Nordal et al. (2009),[13]NVE(2012),[14]Thakur (2012).

After an initial slide and favorable topography, stability of the back scarp is vital in the successive development of a landslide (Mitchell & Markell 1974; Lebuis et al. 1983; Tavenas et al. 1983; Karlsrud et al. 1985; Leroueil et al. 1996). The stability of back scarp is quantified using a parameter referred to as stability number (*Nc*) and is defined as $\gamma H/c_{ui}$ (Bjerrum 1955, Trak and Lacasse (1996). Leroueil et al. (1996) suggests that a significant post-failure movement (retrogression) of soil mass could happen if the stability of the area behind the initial slide zone has $Nc > 4$ if $Ip \sim 10$ and $Nc > 8$ if $Ip \sim 40$. It is interesting to analyze sensitive clays from these perspectives and observe whether sensitive clays behave similarly to quick clays. In the following section, this issue is investigated by analyzing data from one well-documented landslide.

3.1 Lersbakken landslide

Lersbakken area is located south of Trondheim in the central region of Norway. A landslide also known as the lersbakken landslide occurred in 1989 beside a municipality (Heimdal) road. The scar of the landslide is shown in Figure 3. The light-grey zones (or blue in the color prints) represent the areas mapped as sensitive clays, and the dark-grey zones are the slides that have occurred over the years and parallel to Heimdal Road. A water channel about 25-30 m in width flows along the Heimdal road. Most of these landslides have occurred because the canal has been actively eroding the toes of the slopes.

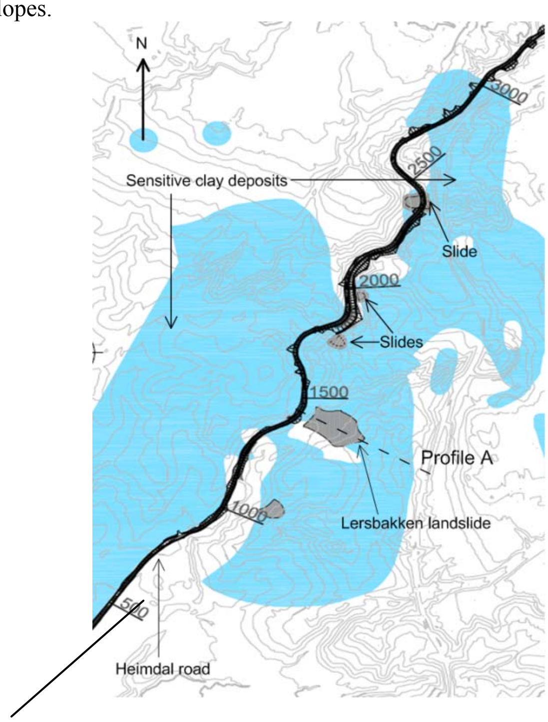

Figure 3 An overview of the Lersbakken slide and the surrounding area (scale1:30000). The Heimdal road profile is presented in the figure using a thick black line along with a marking indicating the road lengths in meters (After NPRA, 2010).

Figure 4 provides a closer view of the slide area shown in Figure 3, and Figure 5 shows a cross-sectional view of the slide area. The scar of the Lersbakken slide in 1989 is approximately 120 m wide and 140 m long along the slope. The slide was a flake-type slide with a sliding zone located 6–8 m below the surface. The slide debris moved (L_F) toward the water canal, approximately 10–15 m from the original location. The reason for the initiation of the slide is unknown. The slide scarp height was between 10 and 12 m, and the volume of the slide was in the order of 70–80 x 10^3 m^3. After the slide, field and laboratory tests were conducted to investigate the site condition. Results of the test results are presented and discussed by Kummeneje (1989), Thakur et al. (2012) and Thakur and Degago (2012). The results of the measurements are presented in Figure 6. An approximately 10 m thick layer of quick clay (having $c_{ur} < 0.5$ kPa) is sandwiched between a sensitive clay layer (above) and an over-consolidated clay layer (beneath).

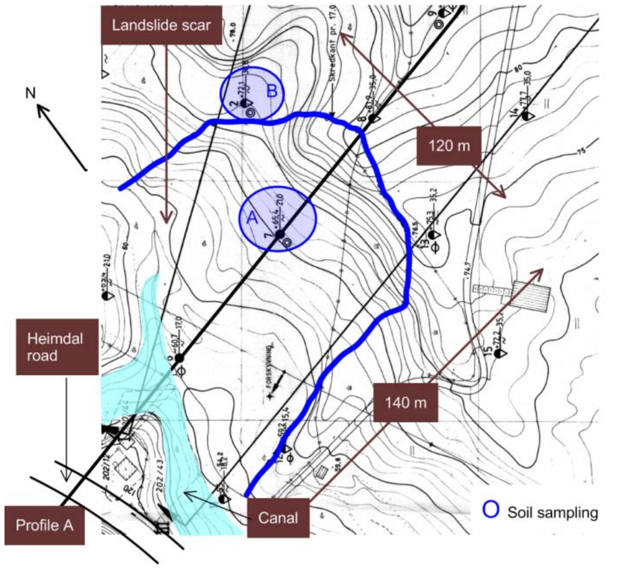

Figure 4 An overview of the Lersbakken slide and the surrounding area (After Kummeneje, 1989).

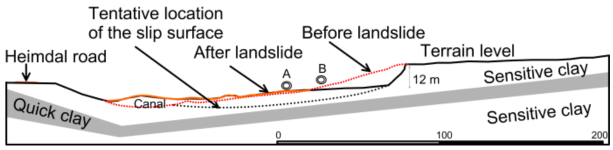

Figure 5 Profile A from the Lersbakken slide

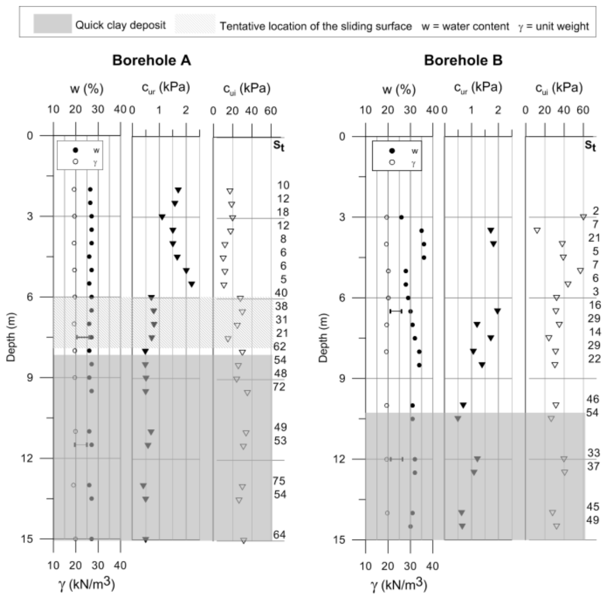

Figure 6 Soil properties versus depth from two representative boreholes; (A): located in the initial Lersbakken slide area and (B): located just outside the initial Lersbakken slide area. c_{ui} and c_{ur} were measured with the fall cone test. These boreholes are located at two different ground elevations, however the sliding surface observed in the field was located between 6-8 meters below and parallel to the ground surface in accord with a flake-type slide. Therefore, a tentative location of the sliding surface in borehole B is assumed to be 6-8 meters.

A closer look at the laboratory results for two boreholes located by the slide zones revealed several interesting facts. The borehole results for the two locations (Figures 4 & 5), i.e., one inside the slide area (borehole A) and another outside the slide area (borehole B), are shown in Figure 6, respectively. The location of the sliding surface, presented as a shadowed zone in Figure 6, indicates that the slide occurred in the upper sensitive clay layer but not in the quick clay layer ($c_{ur} \leq 0.5$). Therefore, it is interesting to investigate the soil properties for the shadowed zone where the c_{ur} and S_t varies from 0.55 to 0.85 kPa and 21 to 62, respectively, for Borhole A. These clays are classified as brittle clays in Norway since they have $S_t > 15$ and $c_{ur} < 2$ kPa (Thakur et al. 2012). Since borehole A is located inside the slide scarp it is interesting to examine the soil properties of the slide debris, i.e. the material above the sliding surface. This would help to understand as to why the slide area was limited to the initial slide. The slide debris which were sensitive in nature has rather high c_{ur} between 1.0 to 2.1 kPa and low and S_t which varies from 5 to 40. Similarly, borehole B, Figure 6, shows that the first 12 m of the soil layer is sensitive in nature. For this layer, c_{ur} varies from 1.1 to 1.9 kPa, and S_t varies from 16 to 29. However, no retrogression was observed in the field past this point. This could be attributed to the fact that the slide debris from the initial slide area were difficult to remold and therefore difficult to flow out of the slide area. It is important to highlight that favorable topography is critical factor in movements of the slide debris that allows further retrogression of landslides. This effect can be appreciated in relation to other Norwegian landslides like the Baastad landslide in 1974 and the Byneset landslide in 2012. In these landslides the topographical aspects were similar to the Lersbakken landslide and the retrogression distance between 300-700 m and run-out distance between 600-870 m. The obvious difference between these two and the Lersbakken landslide is related to the type of material involved in the slide. The Baastad and Byneset landslides occurred in the material which had remolding shear strength less than 0.5 kPa (quick clays). The *Nc* value for the Lersbakken slide was 7.6 (where the total unit weight of the soil mass was $\gamma = 19.0$ kN/m^3, the height of the head wall *H* was 12 m, and the average c_{ui} was 30 kPa). Despite *Nc* being larger than 4, no retrogression was observed for the Lersbakken slide.

This particular case indicates that the soil index parameter like c_{ur} is one of the key indicators of potential for the occurrence of landslide in sensitive clays. Quantitatively speaking, c_{ur} represents flow behavior consistency i.e. the ease with which a material can flow. It is interesting to continue this investigation to assess the flow behavior of sensitive clays using the index parameters related to the remolded state of sensitive clays.

4. ASSESSMENT OF FLOW SLIDES USING SOIL INDEX PARAMETERS

Remolded shear Strength (c_{ur}) has been often used in the assessment of flow slides in sensitive clays. Mitchell and Markell (1974) suggest a direct relationship between c_{ur} and the retrogression distance (L_R), see Figure 7. Based on the landslide data, Lebuis et al (1983) also suggested that $c_{ur} \leq 1$ kPa may define the threshold limit for occurrence of flow slides. They suggest that flow slides with an $L_R > 100$ m are observed for $c_{ur} < 1$ kPa. No retrogression was observed or slides were limited to initial slide for sensitive clays with $c_{ur} > 1$ kPa. Figure 7 shows, a trend between c_{ur} and L_R, that the extent of flow slide decreases with increasing remolded shear strength for both Norwegian and Canadian sensitive clays.

Lebuis et al. (1983), Locat and Demers (1988), Leroueil et al. (1996) and Leroueil (2001) showed that Canadian sensitive clays with $I_L > 1.2$ are susceptible to flow slides. This finding is also in agreement with the landslide data presented in Table 2. It must be noted that, according to the correlations $I_L > 1.2$ is only possible for $c_{ur} < 1$ kPa. In other words, the findings by Mitchell and Markell (1974), Leroueil et al. (1983), Tavenas et al. (1983) and Locat and Demers (1988) are in agreement with each other. These observations advocate that c_{ur} and I_L must be closely connected as shown in Figure 8. In 1983 Leroueil et al. proposed a relationship between c_{ur} and I_L (Eqn.1);

$$c_{ur} = (I_L - 0.21)^{-2} \quad (1)$$

Later in 1988, Locat and Demers presented a slightly modified relationship (Eqn. 2)

$$c_{ur} = 1.46\, I_L^{-2.44} \quad (2)$$

Here c_{ur} is in kPa.

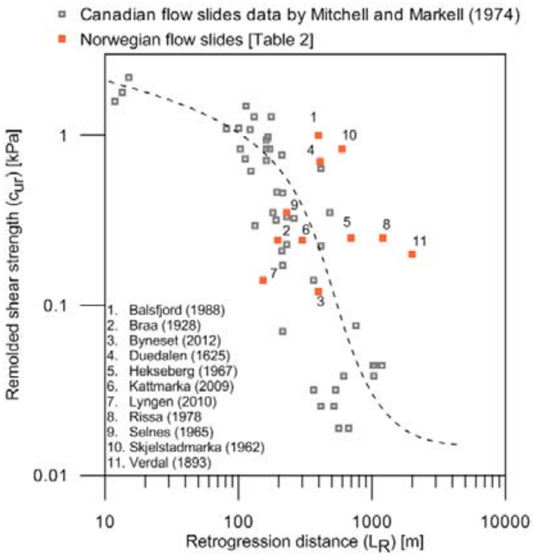

Figure 7 Flow slide as a function of remolded shear strength

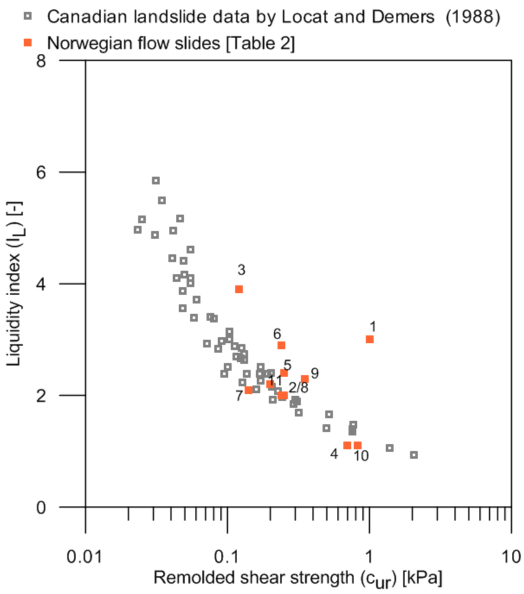

Figure 8 Relationship between c_{ur} and I_L for Norwegian and Canadian sensitive clays

These relationships are valid for a I_L between 1.5 to 6. The relationship by Locat and Demers (1988) can be used to compute c_{ur} or S_t of sensitive clays having c_{ur} values lower than the lower limit of the Norwegian fall cone test apparatus, (i.e. 0.1 kPa). Accuracy of these relationships is evaluated in relation to the Norwegian sensitive clays presented in Table 2. The measured c_{ur} values using the fall cone method for the Norwegian sensitive clays shown in Table 2 is compared, in Figure 9, with the c_{ur} values estimated based on Eqn. (1) and (2). In an ideal situation, no deviation between the measured and the estimated c_{ur}, presented using a dotted line on Figure 9, should be seen. In relation to the dotted line, the figure shows some deviation between the measured and the estimated c_{ur} for the Norwegian sensitive clays. It can also be noted from Figure 9, that Eqn. (1) estimates slightly higher c_{ur} when compared to Eqn. (2).

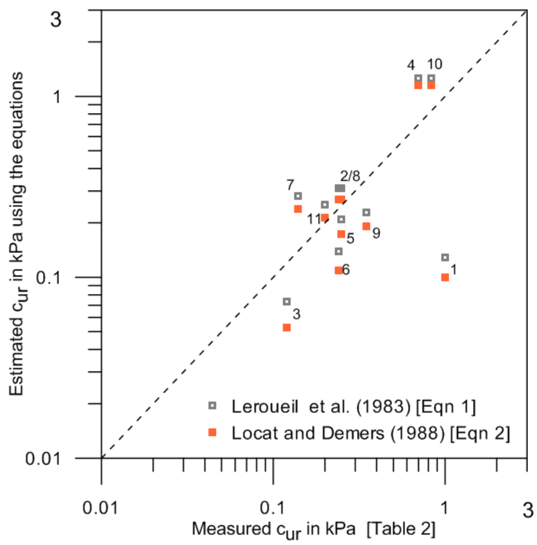

Figure 9 A comparison between the measured c_{ur} and the empirically estimated c_{ur} for the Norwegian sensitive clays presented in Table 2

I_L and c_{ur} based criteria have been widely adopted to study the flow slide potential of sensitive clays, However, the measurement of I_L demands determination of three parameters a priori, i.e. liquid limit (w_l), plastic limit (w_p) and natural water content (w). Notably the conventional thread-rolling method of determining w_p has a significant drawback as it can easily be biased by subjective judgment (Whyte 1982; Feng 2000; Sivakumar et al. 2009). Also, c_{ur} is usually measured using the fall-cone test, a point based measurement system, which may not necessarily be representative of a large soil volume. Keeping this in view this work proposes a new test procedure, the quickness test, to evaluate the flow slide potential of sensitive clays. The proposed test approach is further illustrated with tests.

5. QUICKNESS APPROACH

In this section, a simple test procedure known as the quickness test is described and test results performed using this procedure are presented. The quickness test aims to provide the basis for a physical understanding of flow behavior of fully remolded sensitive clays using a new type of geotechnical engineering test. Additional description on the test methodology can be referred to Thakur and Degago (2012).

5.1 Test procedure

The quickness test is based on the concept of the slump test that is used to measure the consistency of freshly mixed concrete. Quickness test is performed by filling an open ended cylinder with remolded sensitive clay, then slowly lifting the cylinder, and finally measuring the deformation (height and lateral spreading) as the material is subjected to flow. Two different cylinder sizes were used in this study. The small cylinder had size as the diameter (D_o) = 65 mm and height (H_o) = 45 mm. The large cylinder had D_o = 100 mm and H_o = 120 mm. The large cylinder has the same size as the cylinder used for the standard proctor tests. Figure 10, taken from Thakur and Degago (2012), shows the concept of the proposed quickness test. The thoroughly remolded material is placed into the cylinder, leveled off, and allowed to flow outward as the cylinder is slowly lifted upward with minimum disturbance to the sample. The difference in height between the cylinder and the slumped material (H_o-H_f) is measured. The outward flow spread diameter (D_f) is also noted. The quickness (Q) in % is defined as;

$$Q = [1 - H_f/H_o] \times 100 \tag{3}$$

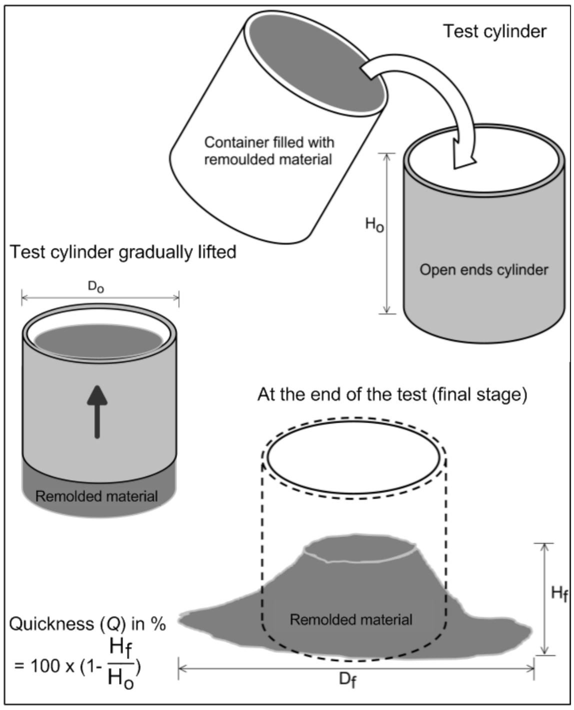

Figure 10 Quickness test procedure. (After Thakur and Degago 2012)

5.2 The tested material

Quickness tests were performed on sensitive clay samples collected from three different landslide locations in the central Norway. These sites have been studied extensively in connection to landslide hazards. Laboratory index properties of the sampled material are presented in Table 3. Liquid limit (w_L), c_{ui} and c_{ur} of the tested material were obtained using the fall-cone method as described by the Norwegian National Standard NS-8015. Representative consolidated undrained triaxial test results at different depths from each three location are presented in Figure 11. It can be seen that these sensitive clays are strain softening materials. However due to test limitations the axial strains that could be run were limited to 10%.

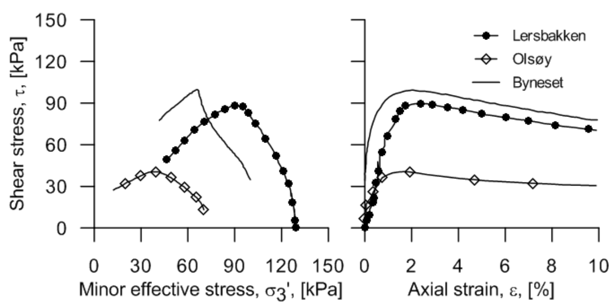

Figure 11 Results of consolidated undrained triaxial tests on sensitive clay samples taken from different depths.

Table 3 Engineering characterization of the tested material

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

The characterization of the sensitive clays, presented in Figure 11 and Table 3, is meant to provide background information for further evaluation of the sensitive clays with respect to their quickness values. It is worthwhile to notice that the clay content within the investigated soils vary significantly as compared to other index properties.

5.3 Results and Observations

Quickness tests were performed on more than 60 different samples extracted from Lersbakken, Byneset and Olsøy landslide locations. A series of pictures taken during the quickness test on Byneset clay samples, with various values of c_{ur} are shown in Figure 12. The figure shows slump and spread observed at selected stages of the tests given as the percent ratio of the height lifted to the cylinder height (H_o). Thakur and Degago (2012) and Thakur et al. (2014) present similar visual representation of the Lersbakken and Olsøy clay. The observations during a quickness test conducted on Lersbakken and Olsøy clay showed that sensitive clays with $c_{ur} \approx 0.5$ kPa were not as fluid as they were originally assumed and sensitive clays with 0.5 kPa < c_{ur} < 1.0 kPa were semisolid in nature. In line with these observations, the Byneset clay samples with c_{ur} < 0.1 kPa, also seemed to be more like a soup as reported by Mitchell and Soga (2004). As the c_{ur} increases from 0.2 kPa towards 1 kPa, the remolded material increasingly showed less viscous behavior and for a c_{ur} > 1.0 kPa little or no flow is observed (Figure 12). This simple test could indicate why soft sensitive clays with a c_{ur} > 1 kPa are less likely subjected to a large retrogression or run-out.

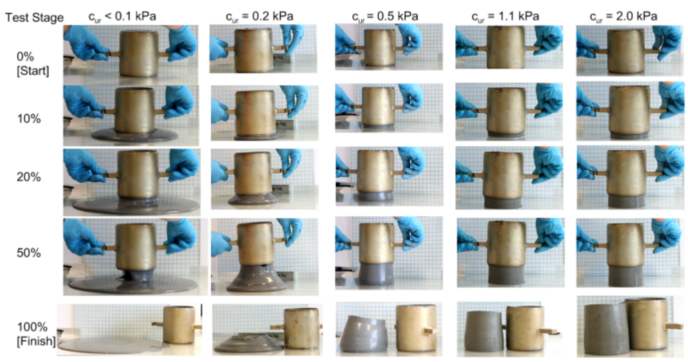

Figure 12 Slump and spread observed at different test stages (from the start to the end of the Quickness tests) for remolded Byneset clays. Test stage (in %) indicates the extent to which a test is accomplished e.g. test stage 0 %, 50% and 100% indicates the start, the half way and the end of the test, respectively

Figures 13-15 presents *Q* versus c_{ur} for various sets of tests on the Lersbakken, Byneset and Olsøy clays performed with two different cylinder sizes. Clay samples with c_{ur} > 1.0 kPa, material flow was not registered irrespective of the size of the test cylinders. Accordingly, this study recommends using a cylinder size 100 mm x 120 mm and proposes some correlations based on this cylinder size because this cylinder size is readily available in connection with the standard proctor test. Interestingly, the flow behavior of sensitive clay is dramatically changing within range 0 < c_{ur} < 0.5 kPa.

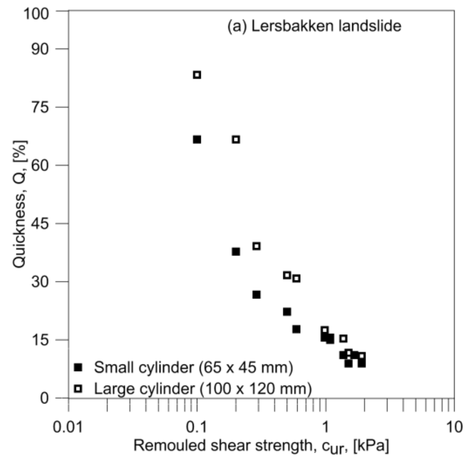

Figure 13 *Q* versus c_{ur} values registered on soil samples taken from the Lersbakken landslide location

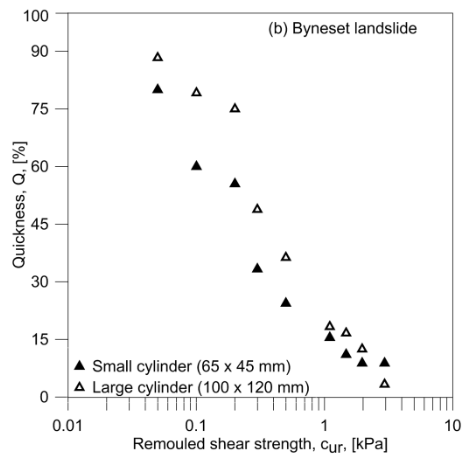

Figure 14 *Q* versus c_{ur} values registered on soil samples taken from the Byneset landslide location

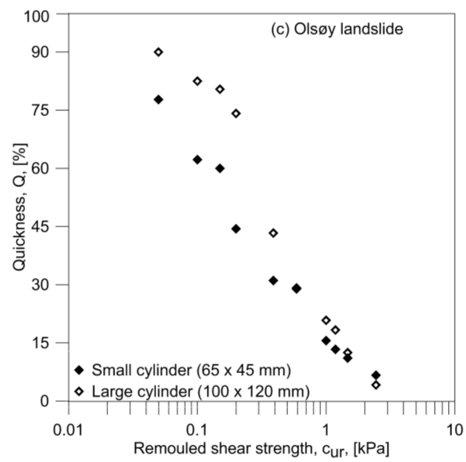

Figure 15 *Q* versus c_{ur} values registered on soil samples taken from the Olsøy landslide locations

A combined plot is shown in Figure 16 where all the data from the three landslide locations are plotted together. The Figure presents the lower and the upper bound Q values observed for various c_{ur} of the tested material. Thakur and Degago (2012) suggests considering the lower bound quickness in evaluating flow slide potentials since it provides a conservative estimate. It can be noticed from the quickness test results shown in Figures 13-16 that all Lersbakken, Byneset and Olsøy materials have nearly identical responses and the lower bound Q = 15 % corresponds to c_{ur} = 1 kPa for all the three sensitive clays.

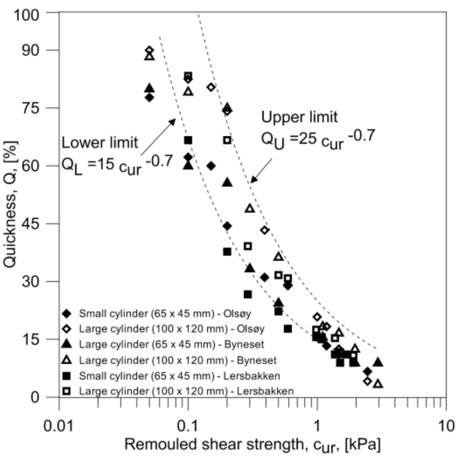

Figure 16 Compilation of Q versus c_{ur} values registered on soil samples taken from the three landslide locations

6. APPLICABILITY OF QUICKNESS TEST

Suitability of quickness value (Q) as compared to remolded shear strength (c_{ur}) in relation to assessment of flow behavior of materials is briefly discussed.

Flow behavior of remolded sensitive clays is difficult to interpret only using the numerical values of c_{ur} as seemingly small change could imply significant alteration in flow behavior of sensitive clays. For example, a significant change in the flow behavior of the sensitive clay from the Byneset landslide is observed for a small variation of c_{ur}, i.e. from < 0.1 to 0.2 kPa and 0.2 to 0.5 kPa. In this case, the significant behavioral change is reflected by the quickness test visually as well as numerically as Q varies from 88% to 75% and 36% to 75%, respectively. The quickness test amplifies the small range of c_{ur}, i.e. from 0 to 2.0 kPa, to a larger scale, almost 0 to 100% (Thakur and Degago, 2012). Quickness test therefore gives a better visualization of the flow behavior of sensitive clays where small c_{ur} values have large implications in regards to understanding the potential for retrogressive landslides. In contrast to the conventional c_{ur} and I_L based approaches, the quickness test is a soil volume based approach and has an added advantage of qualitative description that provides a better visualization with respect to understanding of flow slides. From this angle, it can also be said that slight variation in the estimated c_{ur} using I_L according to the Eqns (1) and (2) by Leroueil et al. (1983) and Locat and Demers (1988), respectively have significant impact on Q values. These observations also suggest that a better correlation between c_{ur} and I_L must be developed for Norwegian sensitive clays.

In general, both c_{ur} and Q principally explains the same soil characteristic through different test approaches. The fall-cone test is a point specific method calibrated against the undrained shear strength of soil under undisturbed and remolded state; whereas, the quickness test gives a value that is representative of the volume of the material tested. In contrast to the fall-cone test, the quickness test has an added advantage of qualitative description that can provide a better visualization with respect to understanding flow slide (Thakur and Degago, 2012). It is worthwhile to note that quickness test is invariant to sample extraction method as it is based on remolded samples. This implies that a wide range of sample extraction methods can be used to perform quickness test. A potential limitation at this stage is that it needs large quantity of samples as compared to fall cone test. However, development of quickness test is an ongoing process and smaller cylinders may need to be considered in the future along with appropriate calibration and verifications.

The quickness approach is meant to establish a rapid method to assess the potential for flow slides in materials out in the field. By doing so, the laboratory apparatuses required to perform c_{ur} and I_L will not be needed. In fact, c_{ur} and I_L can be back calculated from the quickness value. Furthermore, the quickness method can be used not only for sensitive clays but also for other flowable materials like in case of dredged materials, soft seabed sediments, mining wastes and loose fills. The compaction of the remolded material, when the cylinder is being filled or the delay between sample setup and the test, which may increase the resistance, has not be an issue with remolded sensitive clays. However, while dealing with other permeable material this aspect needs to be addressed.

7. EVALUATION OF FLOW SLIDE POTENTIALS

Significance of quickness test is discussed using the Norwegian flow slides given in Table 2. The Q values for each flow slides is estimated based on the corresponding c_{ur} values and using a lower bound correlation shown in Figure 16 ($Q = 15c_{ur}^{-0.7}$). The estimated Q values of the Norwegian flow slides are shown in Figure 17. Based on the quickness test results and the data from the Norwegian landslides, two distinct regions are shown in the Figure 17. These regions indicate the potential for occurrence of flow slides based on Q values. Accordingly, large flow slides are less likely to occur when Q < 15 % (or c_{ur} > 1 kPa) and in this case the slide will be limited to an initial slide only. However, for Q > 15 % (or c_{ur} < 1 kPa), a flow slide is possible. These observations are in line with Lebuis et al. (1983), Leroueil (2001), Thakur and Degago (2012) and Thakur et al. (2014).

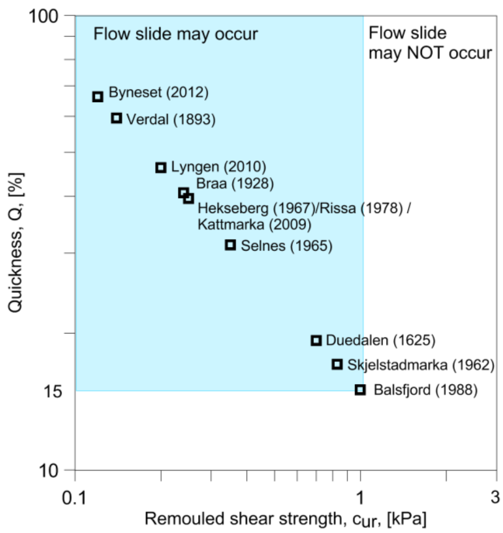

Figure 17 Estimated Q values for Norwegian landslides given in Table 2 and quickness based criteria for occurrence of flow slides

8. CONCLUSIONS

Literature indicates that flow slide is less likely to happen for sensitive clay with c_{ur} > 1 kPa. This has been validated in light of observations from a well-documented landslide. This work presents a laboratory procedure that focuses on the remolded behavior of sensitive clays in terms of a numerical value referred to as quickness, Q. The quickness test was carried out on more than 60 samples from three landslides sites. These results illustrate why sensitive clays with Q < 15 % (or c_{ur} > 1 kPa) are not susceptible to flow slides. Accordingly, this study advocates that Q < 15 % (or c_{ur} > 1 kPa) to be the threshold limit where the extent of a landslide is limited to an initial slide.

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