A new approach to assess the potential for flow slide in sensitive clays

Une nouvelle approche pour évaluer le potentiel d'écoulement des argiles sensibles

Thakur V., Degago S.A., Oset F., Dolva B.K., Aabøe R.
Geotechnical section, Norwegian Public Roads Administration

ABSTRACT: Sensitive clays could constitute a major threat to nearby infrastructure due to potential flow slides. A key question is if all sensitive clays have the same potential to retrogress to the same extent and the significance of remoulded shear strength (c_{ur}) in flow slides. This paper proposes a new approach to asses the potential for flow slides and in doing so presents a new laboratory test procedure referred to as the quickness test. The test focuses on remoulded behaviour of sensitive clays in terms of a numerical value referred as quickness (Q). Sensitive clay samples were collected from three different landslide locations. The quickness test was used to demonstrate why sensitive clays with c_{ur} >1 kPa are not susceptible to flow slides. Based on this study, it is possible to state that a Q < 15 % or c_{ur} > 1 kPa seems to be the threshold limit above which the extent of the retrogression of a landslide is limited to the initial slide. This criteria has been supported using data available from several Norwegian landslides in sensitive clays.

RÉSUMÉ : Les argiles sensibles pourraient constituer une grave menace pour les infrastructures en raison de coulées potentielles. Une question clé est de savoir si toutes les argiles sensibles ont un potentiel de rétrogression équivalent et de d'estimer l'amplitude de la résistance de cisaillement remaniée (c_{ur}) des les coulées. Cet article propose une nouvelle approche pour évaluer le potentiel de coulées et présente ainsi une nouvelle procédure de laboratoire appelée le test de rapidité. Le test se concentre sur le comportement de l'argile sensible remaniée en termes de valeur numérique dénommée rapidité (Q). Des échantillons d'argiles sensibles ont été recueillis à partir de trois sites différents où il y a eu des glissements de terrain. Le test de rapidité a été utilisé pour démontrer pourquoi les argiles sensibles avec c_{ur} > 1 kPa ne sont pas sujettes à des coulées. Sur la base de cette étude, il est possible d'affirmer que Q <15% ou c_{ur} > 1 kPa semble être le seuil au-delà duquel l'ampleur de la rétrogression d'un glissement de terrain est limitée à la rupture initiale. Ce critère se base sur des données disponibles à partir de plusieurs glissements de terrain dans les argiles sensibles norvégiens.

KEYWORDS: Flow slide, sensitive clays, quickness, remolded shear strength, landslide.

1 INTRODUCTION

Soft sensitive clays are normally associated with loss of stability as well as substantial ground deformation, which can lead to structural damage and jeopardize the overall stability of an area. It is worth mentioning the statement by Bhishop in 1973 that "*Rotational slips alone may cause damage to services and property, but seldom involve loss of life. It is the subsequent development into a flowslide which has been responsbile in each case where disaster has occured"*. In the sensitive clay deposits of Scandinavia and eastern Canada, landslides 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.

For flow slides to occur after an initial slide, it is important that at least the following two criteria are fulfilled (Tavenas et al. 1983):

- The slide debris should be sufficiently remoulded.
- The slide debris should be able to flow out of the slide area if remoulded.

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 listed in Table 1, are unlikely to occur. An overview of Norwegian landslides as shown on Table 1 clearly indicates that soft sensitive clays must be handled carefully. However, the term 'sensitive clay' encompasses a wide range of clays depicting significant variations in engineering behaviour such as the remoulded shear strength (c_{ur}). Therefore, a key question is whether all sensitive clays have the same potential to create flow slide and the significance of c_{ur} for occurrence of flow slide? Answer to this question has a direct relavance in the selection of an appropriate safety level for constructions, measures and in hazard mapping.

A relationship between the c_{ur} and the soil sensitivity (S_t) as well as between c_{ur} and the liquidity index (I_L) has been used to evaluate the potential for flow slides in sensitive clays. Mitchell and Markell (1974) suggest a direct relationship between c_{ur}, S_t and the retrogression distance (L). They suggest that landslides with an L > 100 m are observed for c_{ur} < 1 kPa. Retrogression was zero for c_{ur} > 1 kPa. Leroueil et al. (1983) and Locat and Demers (1988) presents correlations between c_{ur} and I_L. The correlations are $c_{ur} = (I_L\text{-}0.21)^{-2}$ and $c_{ur} = 1.46\ I_L^{-2.44}$ respectively. These showed that senstive clays with I_L > 1.2 are susceptible to flow slides. This finding is also supported by the landslide data presented in Table 1. It must be noted that, according to the correlations I_L> 1.2 is only possible when c_{ur} is less than 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 line with each other. Based on the landslide data, Lebuis et al (1983) also suggested that c_{ur} < 1 kPa may define the threshold limit for occurrence of flow slides.

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 (wl), plastic limit (wp) and natural water content (w). Notably the conventional thread-rolling method of determining *wp* has a significant drawback as it can easily be biased by subjective judgement. 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 paper proposes a new test procedure, the quickness test, to evaluate the flow slide potential of sensitive clays. In contrast to the convential 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 provide a better visualisation with respect to understanding of flow slides.

Table 1 Selected large landslides in Norwegian sensitive clays.

No.	Year	Landslide	L_R [m]	c_{ur} [kPa]	S_t [-]	I_L [-]	I_P [%]
1	2012	Byneset	300	0.12	120	3.8	4.8
2	2010	Lyngen	230	0.35	50	1.5	12
3	2009	Kattmarka	300	0.24	63	2.9	8
4	1978	Rissa	1200	0.24	100	2.2	6
5	1974	Baastad	930	0.53	35	1.8	8
6	1967	Hekseberg	230	0.25	100	2.4	4
7	1965	Selnes	700	0.35	100	2.3	7
8	1959	Furre	215	0.2	85	1.3	6
9	1953	Bekkelaget	145	0.2	130	2.4	9
10	1953	Borgen	165	0.7	100	1.2	20
11	1953	Ullensaker	250	0.35	42	1.9	6.7
12	1893	Verdalen	2000	0.2	300	2.2	5

*L_R = Retrogression distance

2 THE QUICKNESS APPROACH

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

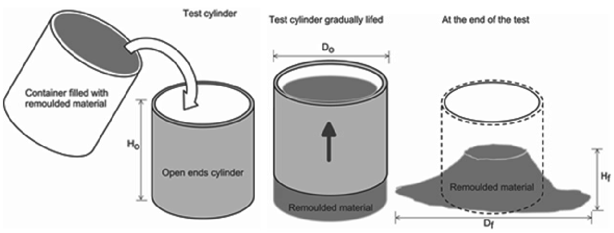

Figure 1. Quickness test procedure (Thakur and Degago, 2012).

2.1 Test procedure

The quickness test is a simple procedure that is performed by filling an open ended cylinder with remoulded sensitive clay, then slowly lifting the cylinder, and finally measuring the deformation (height and lateral spreading) as the material is subjected to flow due to its own weight. The test concept is similar to the slump test for concrete that is used to measure the consistency of freshly mixed concrete. Two different cylinder sizes were used. The dimensions were the diameter (D_o) = 65 mm and height (H_o) = 45 mm for the small cylinder, and D_o = 100 mm and H_o = 120 mm for the large cylinder. The large cylinder has the same size as the cylinder used for the standard proctor tests. Figure 1, taken from Thakur and Degago (2012), shows the concept of the proposed quickness test. The thoroughly remoulded material is placed into the cylinder, levelled 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 [1- H_f /H_o] × 100.

2.2 The tested material

Quickness tests were performed on several sensitive clay samples taken from three different locations in the central Norway. One of the landslides, Lersbekken, have been studied and presented in Thakur and Degago (2012). In this work a similar approach is presented for two new landslide locations Byneset and Olsøy. These sites have been studied extensively in connection to landslide hazards. Laboratory index properties of the sampled material are presented in Table 2. 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.

Table 2 Properties of the tested materials from three different landslide locations

Properties	Lersbekken	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

3 TEST RESULTS AND OBSERVATIONS

Quickness tests were performed on more than 60 different samples extracted from Lersbekken, Byneset and Olsøy landslide locations. A series of pictures taken during the quickness test on two Byneset clay samples, with c_{ur} = 0.1 kPa and c_{ur} = 1.0 kPa, are shown in Fig. 2. The figure shows slump and spread observed at selected stages of the tests given as the precent ratio of the height lifted to the cylinder height (H_o).

Previous observations during a quickness test conducted on Lersbekken 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 (Thakur and Degago, 20120). In line with this observations, the Byneset and Olsøy clay samples with c_{ur} < 0.2 kPa, seemed to be more like a soup as reported by Mitchell and Soga (2004). The registered collapse of the remoulded material was negligible when the remoulded sensitive clay had c_{ur} > 1.0 kPa.

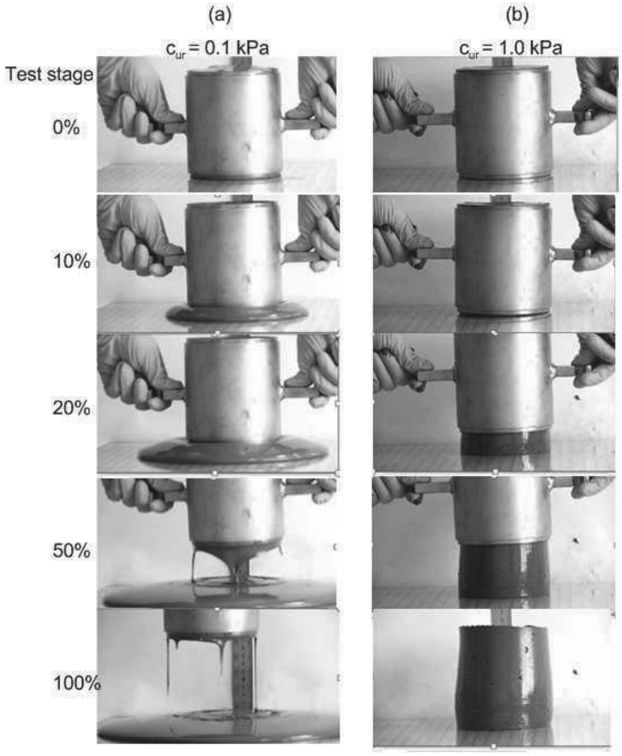

Figure 2. Slump and spread observed from the start to the end of the Quickness tests for remoulded Byneset clays (a) c_{ur} = 0.1 kPa and (b) c_{ur} = 1.0 kPa.

A typical flow and spread behaviour of two remoulded clays from the Olsøy site are presented in Figure 3. The tests on Olsøy clay shows that the remolded material with c_{ur} < 0.2 kPa seemed to be more like a soup, Figure 3(a). 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 3(b). This simple test indicates why soft sensitive clays with a c_{ur} > 1 kPa are less likely subjected to a large retrogression or run-out.

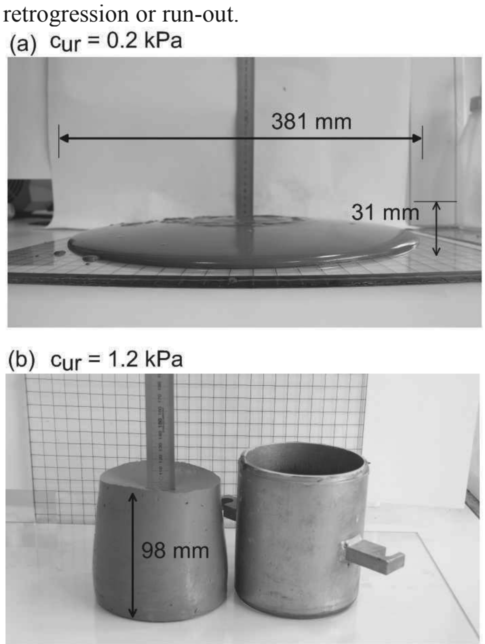

Figure 3. Flow and spread behaviour of the two remoulded Olsøy clays having (a) c_{ur} = 0.2 kPa and (b) c_{ur} = 1.2 kPa.

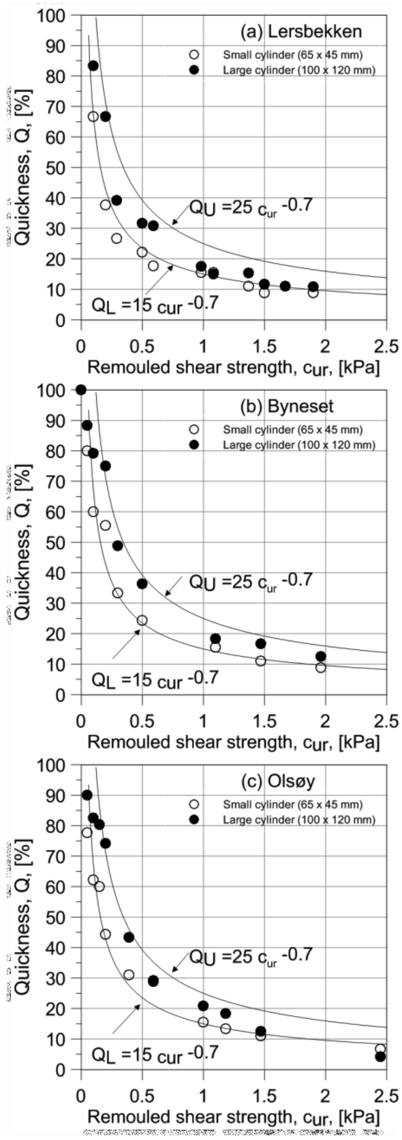

Figure 4. Q versus c_{ur} values registered on soil samples taken from a) Lersbekken b) Byneset and c) Olsøy landslide locations.

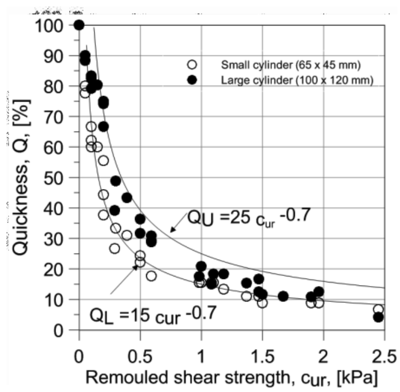

Figure 5. Compilation of Q versus c_{ur} values registered on soil samples taken from the three landslide locations.

Apparently, the flow behaviour of the Lersbekken, Byneset and Olsøy clay is identical. Figure 4 presents Q versus c_{ur} for various sets of tests on the Lersbekken, Byneset and Olsøy clays performed with two different cylinder sizes, 100 mm x 120 mm, 65 mm x 45 mm. For the major area of interest, i.e. 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. The Figures presents the lower and the upper bound Q values observed for various c_{ur} of the tested material. A combined plot is shown in Figure 5 where all the data from the three landslide locations are plotted together.

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 (Figure 4 and 5) that all Lersbekken, 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.

4 SUITABILITY OF QUICKNESS TEST

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

Fluidity of sensitive clays is difficult to interpret by small numerical values of c_{ur} because a seemingly small change could imply significant alteration in flow behaviour of clay. For example, a significant change in the flow behaviour of the sensitive clay from the Lersbekken site is observed for a small variation of c_{ur}, i.e. from 0.5 to 0.2 kPa. In this case, the significant behavioural change is reflected by the quickness test visually as well as numerically Q varies from 32% to 67% (Thakur and Degago, 2012). The quickness test amplifies the small range of c_{ur}, i.e. from 0 to 2.0 kPa, to a larger scale, 0 to 100%. Quickness test therefore gives a better visualisation of the flow behaviour of sensitive clays where small c_{ur} values have large implications in regards to understanding the potential for retrogressive landslides.

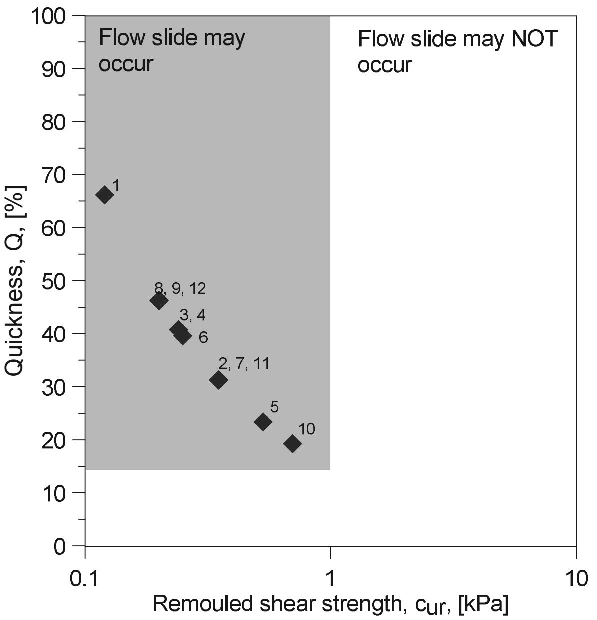

Figure 6. Estimated Q values for Norwegian landslides given in Table 1 and quickness based criteria for occurrence of flow slides.

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 remoulded 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).

5 ASSESMENT OF FLOW SLIDE POTENTIALS

Significance of quickness test is illustrated in relation to assessment of potential for flow slides using the Norwegian landslides given in Table 1. In doing so the Q values for each landslides is estimated based on the corresponding c_{ur} values and using a lower bound correlation shown in Figure 5 ($Q = 15\ c_{ur}^{-0.7}$). The estimated Q values of the Norwegian landslides are shown in Figure 6 where the numbers corresponds to the landslide numbers as listed in Table 1.

Based on the quickness test results and the data from the Norwegian landslides, two distinct regions are shown in the Figure 6. These regions depict 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. Based on the retrogression length (L_R) of the Norwegian landslides studied in this work, 15 % < Q < 25 % (or 0.5 kPa < c_{ur} < 1 kPa) mostly corresponds to a flow slide with L_R < 250 m while Q > 25 % (or c_{ur} < 0.5 kPa) corresponds to a flow slide with L_R > 250 m. Effort is being made to establish a correlation between L_R and Q using several landslide data, however at this stage no specific recommendation is made.

6 CONCLUSIONS

This paper presents a new laboratory procedure that focuses on remoulded behaviour of sensitive clays in terms of a numerical value referred to as quickness (Q). The quickness test was used to demonstrate why sensitive clays with c_{ur} > 1.0 kPa are not susceptible to flow. This particular study shows that a Q < 15% or c_{ur} > 1.0 kPa seems to be the threshold limit where the extent of the retrogression of a landslide is limited to the initial slide.

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