In-situ determination of disintegration energy for soft sensitive clays

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ABSTRACT
An accurate assessment and prediction of retrogressive landslides in sensitive clays is a complex and demanding task. Still, there have been several attempts to assess flow slide potentials by looking at certain aspects of sensitive clays of which one of them is studying the energy involved in the disintegration of sensitive clays from an intact to a remolded state. This energy is referred to as disintegration energy. Estimation of disintegration energy in the laboratory is not a straightforward task. Moreover, the challenges associated with the sampling of soft sensitive clays complicate the overall picture. Therefore, in this study an effort was made to perform an in-situ measurement of the disintegration process of Norwegian sensitive clays using the electric vane shear apparatus. The significance of the testing procedure and the results are discussed in light of available analytical and laboratory test results. This is also evaluated in light of previous work reported in the literature.

RÉSUMÉ
L'évaluation et la prévision précise des glissements de terrain rétrogressifs dans les argiles sensibles sont des tâches complexes et difficiles. Il y a pourtant eu plusieurs tentatives pour évaluer les potentiels de glissements de terrain en considérant certains aspects des argiles sensibles, par exemple l'étude de l'énergie nécessaire au remodelage des argiles sensibles de l'état intact jusqu'à l'état remodelé. Cette énergie est appelée l'énergie de remodelage. L'estimation de l'énergie de remodelage en laboratoire n'est pas simple à réaliser. De plus, les défis associés à l'échantillonnage des argiles sensibles molles compliquent la situation. Par conséquent, cette étude a évalué le processus de remodelage des argiles sensibles de Norvège lors de l'utilisation in situ d'un scissomètre électrique. L'importance de la procédure d'essai et les résultats sont discutés à partir des résultats analytiques et des essais de laboratoire disponibles. Ceci est également évalué à la lumière des travaux antérieurs rapportés dans la littérature.

1 INTRODUCTION

1.1 Background

Retrogressive landslides in sensitive clays are historically known for their ability to cause varying degrees of destruction. Such occurrences often result in large devastating landslides because the involved slide debris can easily be sufficiently remolded to flow out of the slide area, see Figure 1 (e.g., Bishop 1967; Bjerrum 1973; Mitchell and Markell 1974; Lebuis and Rissmann 1979; Tavenas et al. 1983; Thakur et al. 2014a). Therefore, retrogression potential of a landslide must be assessed as a part of the spatial planning for infrastructure developments including road, railroad residential and commercial buildings in Norway.

A retrogressive type of landslide occurs on seemingly stable slopes as a result of an initial local slide. In highly sensitive clays, flow slides of large extent usually start with an initial slide of limited extent. For such flow slides to occur after an initial slide, it is important that the slide debris should be sufficiently disintegrated or remolded, followed by a possibility to be able to flow out of the slide area (Tavenas et al. 1983; Thakur and Degago. 2013). There may be additional factors, such as the topography and the initial stability of the area behind the initial slide zone. However, flow slides are less likely to occur if sufficient disintegration of sensitive clay does not takes place.

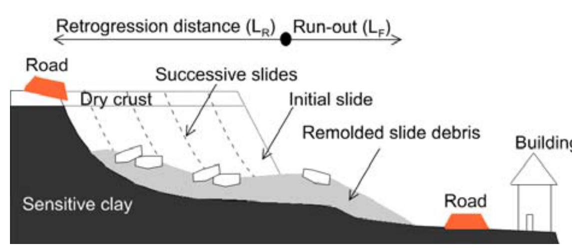

Figure 1. Illustration of flow slides in sensitive clays (Thakur and Degago 2014)

1.2 Research question

In the literature, several indicators of potential for flow slides of sensitive clay exist, e.g. the remolded shear strength (c_{ur}), the liquidity index (I_L), the sensitivity (S_t), the quickness (Q). Although these criteria are useful indicators of the potential of a clay to remold and then flow, these individual geotechnical parameters cannot be used to determine whether a retrogressive landslide will actually occur or not. Another promising approach is to study the disintegration process of sensitive clays. In other words, this demands determination of the disintegration energy which in turn involves an understanding of complete stress-strain behavior of sensitive clays (Figure 2).

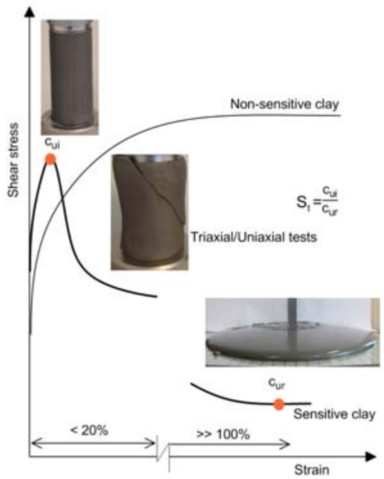

Figure 2. Schematic representations of a soft sensitive clay subjected to deformation; from the intact and the fully disintegrated (remolded) state. (Thakur and Degago, 2014)

Determination of the disintegration energy (DE) of sensitive clay in the laboratory requires some special arrangements so that the specimens can be deformed to their residual strain level. 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 may require very large strain. Ring shear tests, fall cone test or reversal shear box test are often used to achieve a fully residual state. Given the simplicity, the remolded shear strength of sensitive clays is often measured using the fall cone test, however this method does not give any information regarding the level of strain required to attain the fully disintegrated state (e.g. Bjerrum and Kjærnsli 1957; Skempton 1964; Chandler 1966; Leroueil 2001; Mesri and Huvaj-Sarihan 2012).

The majority of Norwegian sensitive clays are soft and low plastic in nature. Therefore, to do a reliable laboratory testing in such material demands an undisturbed sampling followed by a careful handling of the material. However, this is not a straightforward task because of the inevitable sample disturbance resulting from the practical constraints associated with the sampling techniques, transportation methods, storage effects and handling procedures. Figure 3 illustrates this using an example of a low plastic Norwegian sensitive soft clay that is prone to sample disturbance; especially when sampled using tube samplers. In other words, laboratory testing in such material is not free from the effect of sample disturbance. Accordingly, the assessment of disintegration energy may also be biased with the quality of tested samples. Moreover, high quality samples, such as block samples, are time consuming and expensive. In order to overcome these issues, in this study an effort was made to develop a way of determining the disintegration energy in-situ using an electric field vane apparatus. An attempt has been made to establish a complete stress-strain curve for the sensitive clay, i.e. from the intact to the fully disintegrated state. The significance of the testing procedure and the results are discussed and evaluated in light of the available empirical data and the laboratory test results in the literature.

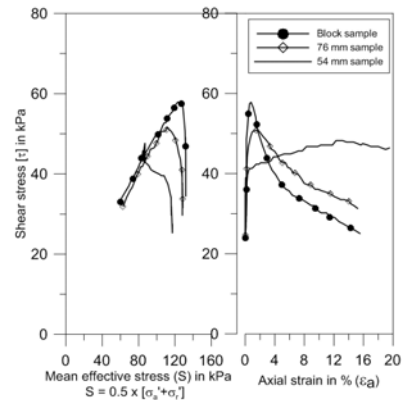

Figure 3. Effect of sample disturbance in sensitive clays taken from 10m depth. Here σ_a' and σ_r' are the effective stresses in the axial and the radial direction, respectively. The presented results are from the Kløfta road project in Norway (Source; NPRA, 2009)

2 DISINTEGRATION ENERGY

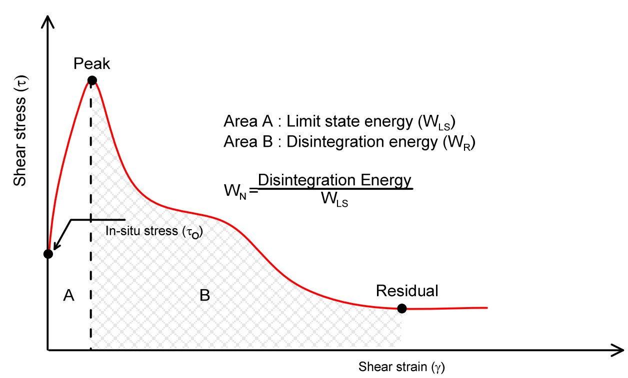

Figure 4. Illustration of disintegration energy concept

The concept of DE is a robust approach to gain an overall mechanical behavior of sensitive clays during the disintegration process. DE is simply defined as the strain energy involved in the disintegration of a sensitive clay. DE of a material can be estimated simply by calculating the area under the shear stress-shear strain curve of the material, see Figure 4.

The energy concept has been a subject of study since the early work by Bishop (1967). Since then (e.g. Eigenbrod 1972; Flon 1982; Tavenas et al. 1983, Yong and Tang 1983; D'Elia et al. 1988; Karlsrud et al. 1985; Leroueil et al. 1996; Leroueil 2001; Hutchinson 2002; Vaunat and Leroueil 2002; Locat et al. 2008; Quinn et al., 2011; Thakur and Degago 2013&2014; Thakur et al. 2014a&b) have studied this concept in relation to the investigation of retrogressive landslides on sensitive clays.

Determination of DE is not a straight forward task. However, Tavenas et al. (1983) did some pioneering work to estimate the disintegration energy of seven different Canadian sensitive clays using different laboratory set-ups. They attempted to simulate different processes by which a sensitive clay may be disintegrated during a landslide event. Accordingly, these processes are the shearing along with continuous straining and displacement along a failure surface, squeezing and extrusion between relatively intact clay blocks, impact of clay block on the bottom of the slide bowl or impact on clay blocks from falling objects or soil. Tavenas et al. (1983) reproduced these processes in the laboratory using some special arrangements, see Figure 5, to estimate the disintegration energy.

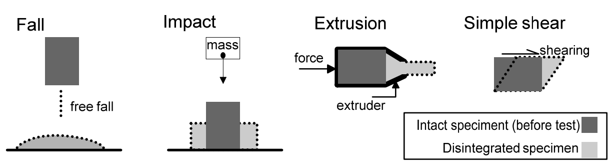

Figure 5. Schematic illustration of processes responsible for the disintegration of sensitive clays involved in a landslide as studied by Tavenas et al. (1983)

The disintegration process induced by the extrusion method required the highest amount of energy, whereas the free fall method disintegrated the tested sample on a much lower energy level. Tavenas et al. (1983) suggest that the extrusion method may overestimate the disintegration energy due to the friction between the tested specimen and the apparatus; while the free fall method may underestimate the same due to a non-uniform disintegration of specimen. Tavenas et al. recommend that the simple shear test was best suited to investigate the disintegration process of sensitive clay samples. Accordingly, simple shear tests were conducted on several samples collected from all seven locations.

Tavenas et al. found that the energy involved in the disintegration process depends on the degree of remolding. This aspect is addressed using the term remolding index (I_r) which refers to the intact and fully disintegrated (remolded) strength of the clays. Accordingly, the remolding index (I_r) was defined as;

$$I_r = \frac{c_{ui} - c_{ux}}{c_{ui} - c_{ur}} \qquad [1]$$

where c_{ui} and c_{ur} are the intact and remolded strength, respectively. c_{ux} is the strength of partly disintegrated specimen. A term called normalized energy per unit volume (w_N) was introduced in their study. This term refers to a ratio between the disintegration energy per unit volume and the energy required to achieve the limit state (W_{LS}).

In the recent years, some researchers have used their footprints to study the retrogressive landslides in Canadian sensitive clay deposits. Some analytical and empirical work has been carried out by Thakur and Degago (2013 &2014); Thakur et al. (2014a&b), however the actual measurement of the DE is yet to be made for the Norwegian sensitive clays.

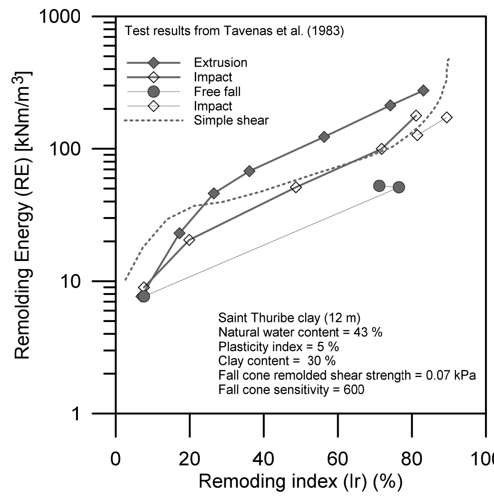

Figure 6. Disintegration energy at different level of disintegration of the Saint-Thuribe specimen tested using different techniques based on the laboratory observation by Tavenas et al. (1983)

3 IN-SITU MEASUREMENT

In-situ determination of the disintegration energy of sensitive clays has not been tried before. In this study an attempt has been made to do this using an electric field vane apparatus.

3.1 Electric field vane

The in-situ measurement of disintegration energy was carried-out using the electric field vane. The device is historically known as a moderately rapid and economical in-situ method for the measurement of undisturbed and remolded shear strength of soft to medium stiff clays. The electric field vane consists of a four-bladed vane (Figure 7) which is pushed and then slowly rotated into a clay layer and the resisting torque is registered. The execution of the vane test today is given in various standards such as ASTM D2573 and EN 1997-2 (A method standard is presently in process (EN ISO 22476-9). The EN 1997-2 only gives an overall guideline to the vane testing method).

The vane blades are positioned at 90° to each other and the common vane height to diameter ratio is two. In this study, a 65 mm diameter and 130 mm high vane were used, At the desired depth, a constant rotation rate of 0.2^{o} per minute was applied. As illustrated in Figure 8, a continuous measurement of the torque was made till the vane is rotated to 360^{o}. The undrained shear strength is interpreted from the measured peak torque. The remolded reading is done after 25 full rotations of the vane. It is important to note that in the electrical vane test it is possible to account for the inherent friction in the rod system. This increases the accuracy of the method, at least for shallow depths.

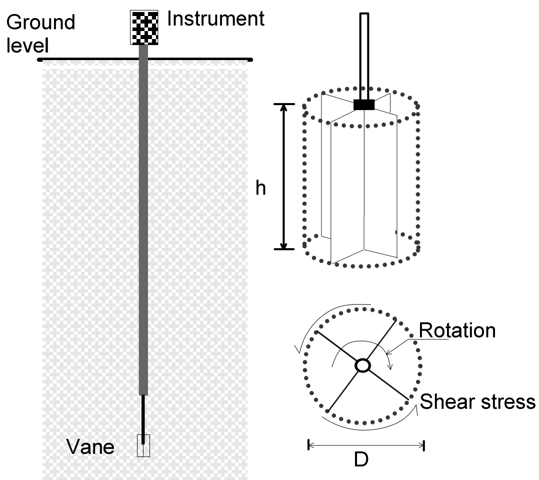

Figure 7. Vane shear apparatus

The registered total torque (T_{tot}) in the field vane test is used to calculate the shear stresses. It must be noted that the total torque per unit volume is equivalent to the disintegration energy.

$$\tau = \frac{6}{7}\frac{T_{tot}}{\pi D^3} \quad [2]$$

The torque required for rotating the wing at a given speed termed the maximum torque and provides a basis for determining the material undrained shear strength $c_{ui,v.}$ At this stage the above equation can be written as;

$$c_{ui,v} = \frac{6}{7}\frac{T_{tot\text{-}max}}{\pi D^3} \quad [3]$$

It must be noted that this equation is based on the following assumptions;

a. The soil is complely undrained during the test i.e. no local drainage of pore water from the shear zones
b. There is no progressive failure in the soils subjected to shear.
c. The failure surface is cylindrical in the shape
d. Isotropic strength condition prevails in the soil volume

The drawbacks of these assumptions on the estimation of undrained shear strength has been widely discussed in the literature. In particular, a recent study by Gylland et al. (2013) shows that some of these assumptions related to the progressive failure and the shape of the failure zones are not necesarily correct.

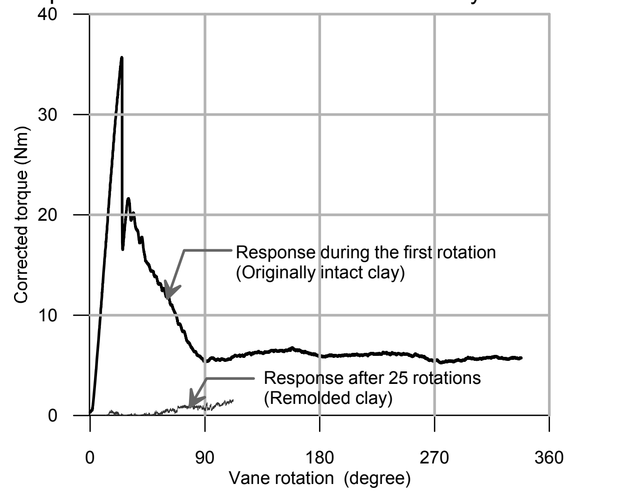

Figure 8. Typical vane shear test result

3.2 Tested materials

The field vane shear tests were carried out at three different sensitive soft clay deposits located in Central Norway. All these tests were carried out at depth 8.5 m below the ground level.

Table 1. Characteristics of the tested soils

Characteristics (%)	Tiller	Klett	Fallan
Natural water content (%)	40	33	33
Unit weight (kN/m^3)	19	20.2	18.8
Salt content (g/l)	1.0	1.0	0.8
Remolded shear strength[1] (kPa)	0.1	0.1	0.2
Fall cone sensitivity (-)	300	240	99
Liquidity index (-)	4.5	2.1	4.4
Plasticity index (%)	5	7	5
Fine silt fraction (%)	62	20	23
Coarse silt fraction (%)	0	11	8
Clay fraction (%)	38	32	34
Overconsolidation ratio (-)	1.3	1.2	3
In-situ effective overburden pressure (σ_{vo}')	86.5	100	87

[1] based on the fall cone test

4 RESULTS

The results of the field vane shear tests in terms of the undrained shear strength calculated using Equation 3 and the corrected vane rotation in radians is presented in Figures 9-11. The field vane measurements beyond θ > 90^{o} (1.57 radians) indicate that the undrained shear strength remains more or less unchanged. Such behavior is believed to result due to the drainage of excess pore water pressure from the sheared zone and is considered to be a major limitation of the test. Therefore, the shear stress – vane rotation response beyond θ > 90^{o} is not considered in the estimation of disintegration energy. Instead, to calculate the total disintegration energy W_R at the fully disintegrated state, a linear extrapolation of the downward curve of the shear stress-radial displacement part is made until the residual shear stress as shown in the Figures 9-11. Measurements of the remolded strength were recorded after 25 manual turns of the vane.

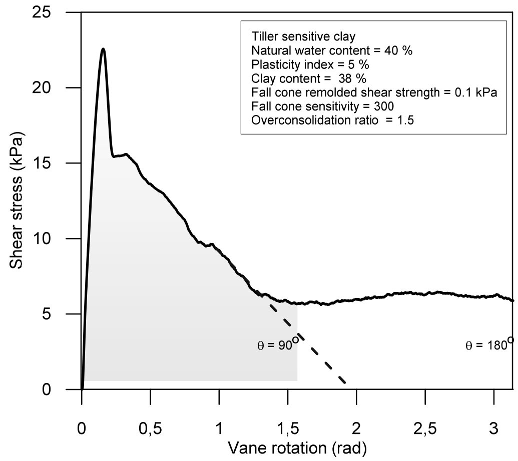

Figure 9. Shear stress-vane rotation curve for the tested Tiller sensitive clay at 8.5 m depth

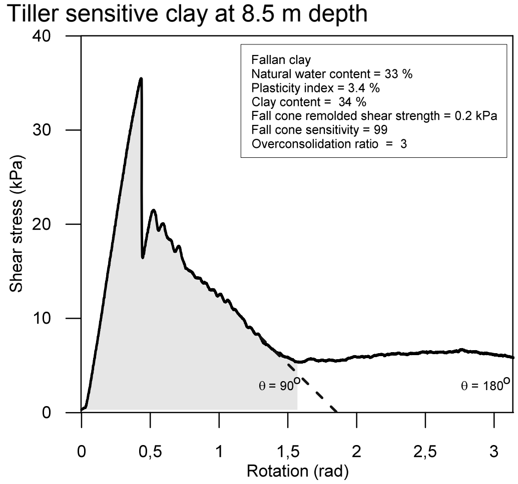

Figure 10. Shear stress-vane rotation curve for the tested Fallan sensitive clay at 8.5 m depth

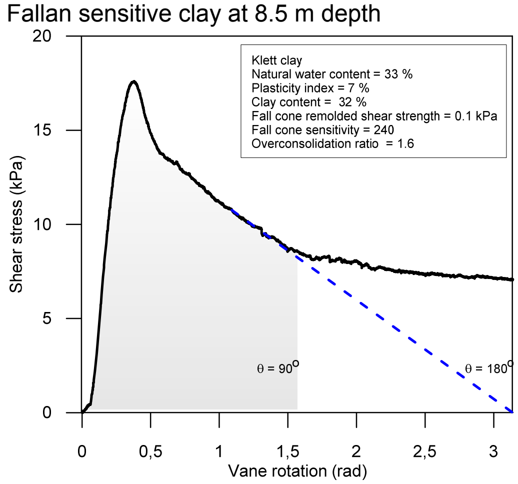

Figure 11. Shear stress-vane rotation curve for the tested Klett sensitive clay at 8.5 m depth

Table 2 Interpretation of vane shear tests

Characteristic (%)	Tiller	Fallan	Klett
Undrained shear strength			
Peak ($c_{ui,v}$)	22.6	35.5	17.6
At $\theta = 90^o$	5.7	5.4	8.6
At $\theta = 180^o$	5.85	5.83	7.1
Fall cone remolded	0.1	0.2	0.1
Vane rotation at the peak (rad)	0.16	0.43	0.38
Remolding index (Ir) at $\theta = 90^o$	75	85	52
Limit state energy (W_{LS}) (kNm/m^3)	2.1	7.3	4.7
Disintegration energy W_{90} at $\theta = 90^o$ (kNm/m^3)	17	21.6	18.6
Disintegration energy W_R at Ir = 100% (kNm/m^3)	18.2	22.9	24.4

4.1 Interpretation of test results

Besides several details associated with the interpretation of vane shear tests as discussed in the literature, this part mainly focuses on the interpretation of remolding index, limit state strain energy and the disintegration energy. The energy was measured simply by calculating the area under the shear stress-rotation curve of the material, Figure 4. Afterwards, these interpretations have been used to establish a relationship between the disintegration energy and the degree of remolding.

The remolding Index (I_r) is calculated based on Equation 1. *Ir* is equal to 0% for an intact clay and 100% for a completely disintegrated clay.

The remolding index, being influenced by the remolded strength c_{ur}, may show misleading behavior at larger depths, i.e. 10-15 m. At these depths, a growing influence of the test equipment is appearing, causing the obtained values to deviate from the remolded shear strength values measured in the fall cone tests. It would hence be better to measure the torque close to the vane tip since one reason for this behavior may be elastic deformations in the rod system. However, this aspect is not investigated further in this paper.

Disintegration of a sensitive clay initiates after the peak shear strength of the material is achieved. Accordingly, Tavenas and Leroueil (1981) suggested a parameter called limit state strain energy (W_{LS}), which is the strain energy required to achieve yielding. They suggested

$$W_{LS} = 0.013\, p_c' \qquad [4]$$

Here W_{LS} is expressed in kNm/m^3 and p_c' in kPa. This equation is valid for Champlain sea clays. In this study W_{LS} is interpreted by calculating the area between the start of the test ($\theta = 0^o$) and the vane rotation corresponding to the peak shear strength under the shear stress- vane rotation curves. This is also shown in Figure 4. The measured W_{LS} values, based on results given in Figures 9 to 11, varied between 3 to 8 kPa. Whereas, Equation 4 is expected to underestimate the W_{LS} value for the Norwegian clays. Similarly, the disintegration energy W_{90} was estimated by calculating the area of the stress-vane rotation curve between the vane rotation corresponding to the peak shear strength and $\theta = 90^o$ (or 1.57 radians). Here, W_{90} refer to the disintegration energy at $\theta = 90^o$.

The test results show a characteristically different behavior when $\theta > 90^o$ i.e. The residual strength being larger than the remolded strength is expected, whereas the constant shear strength being constant may be caused by partial drainage.

In return, the strain softening process in the material has visibly stopped. The shear strength of the clay measured at this stage is much larger than the fall cone remolded shear strength. According to Equation 1 this will result in $I_r < 100\%$ even though the material may be fully disintegrated. To overcome this issue, a pragmatic solution was adopted. The disintegration energy W_R corresponding to a 100% disintegration (I_r = 100%) was estimated including the linearly extrapolated stress-vane rotation curves in the Figures 9-11.

Similar to Tavenas et al. (1983), the disintegration energy is expressed in terms of the normalized disintegration energy which is

$$W_N = \frac{\text{Disintegration energy}}{W_{LS}} \qquad [5]$$

Here W_N is a dimensionless parameter. Based on the earlier observation by Lebuis and Rissmann (1979), Tavenas et al. (1983) postulated that large retrogressive landslides occur if I_r = 70% can be reached for $W_N \leq 40$.

5 DISCUSSIONS

5.1 Disintegration energy

The DE is an indicator of how large amount of potential energy will be consumed in the disintegration of sensitive clays. The interpretation of the field vane tests suggest that it is possible to estimate the energy involved in the disintegration of sensitive clays. This is illustrated in Figure 12 where the W_N is presented with respect to vane rotation. It is shown that W_N corresponding to 90^o rotation varies from 3 to 8.

The I_r at $\theta = 90^o$ varied from 52% for Klett sensitive clay to 90% for Fallan sensitive clay (Table, 2). The lowest W_{90} was estimated for Tiller sensitive clay at 17 kNm/m^3 while the highest was for Fallan sensitive clay at 22 kNm/m^3. The variation between W_{90} and W_R is generally less significant for the Tiller and Fallan sensitive clays as compared to Klett clay. The laboratory studies suggest that the Tiller sensitive clay deposit at depth 8-9 m consists of thin silt layers. In return, these layers help in dissipating more excess pore pressure. This could explain why only 51% disintegration was achieved at $\theta = 90^o$ for this clay.

The W_N is further plotted versus estimated I_r in Figure 13. For the sake of comparison the simple shear test results for seven different Canadian sensitive clays, as reported by Tavenas et al (1983), are also plotted in the same figure. The results trend generally indicates that larger disintegration energy (W_N) is required to attain a higher degree of disintegration (I_r) for the tested clays.

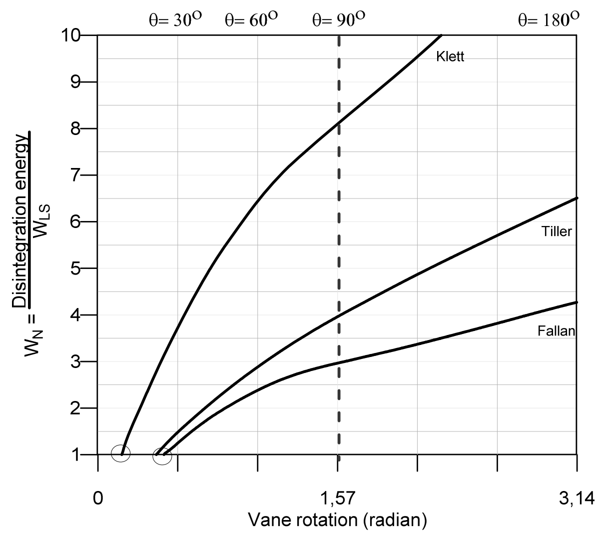

Figure 12. Interpreted W_N based on Figures 9-11

Despite similar trends for the Canadian and the Norwegian sensitive clays, the results indicate that the Canadian clays required much more disintegration energy than the Norwegian sensitive clays to attain the same level of disintegration. At Ir =70%, the W_N ranges from 3 to 8 for Norwegian sensitive clays while it varies from 15 to 135 for Canadian sensitive clays (Figure 13).

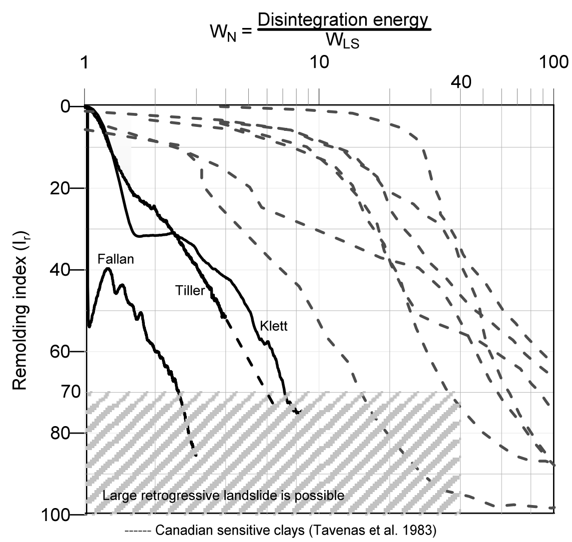

Figure 13. Remolding energy vs remolding index

Tavenas et al. (1983) also postulated that large retrogressive landslides occur if I_r = 70% can be reached for $W_N \leq 40$ (i.e. the hatched zone in the figure). In case of Norwegian data, Ir = 70% is generally obtained at much lower W_N as compared to Canadian sensitive clays. In fact, the tested Norwegian clays attained $Ir \geq 70$ % at $W_N < 10$. Stated differently, if the hypothesis by Tavenas et al. (1983) stands for the Norwegian conditions as well, a low disintegration energy for Norwegian sensitive clays is required for large retrogressive landslides to occur. To investigate this further, W_N at Ir = 70% and the liquid limit are plotted in Figure 14 for the Norwegian and Canadian sensitive clays. The results show some scatter but still indicate a general trend suggesting that material with higher liquid limit require higher W_N to attain Ir = 70%. This trend is in line with other studies (Leroueil et al. 1996, Locat et al. 2008, Thakur and Degago (2013), and Thakur et al. (2014a&b))

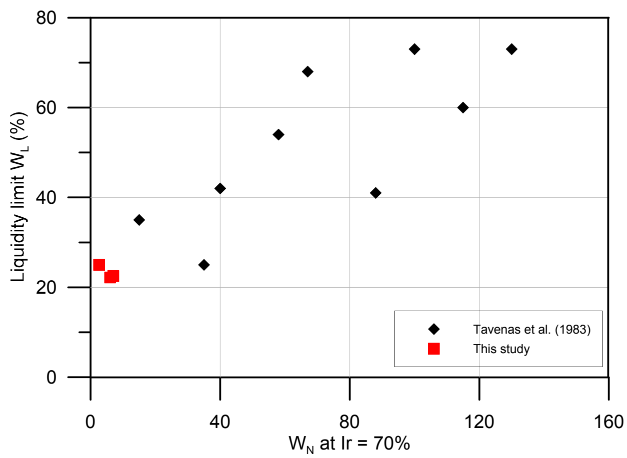

Figure 14. Disintegration energy at Ir = 70% as a function of liquid limit

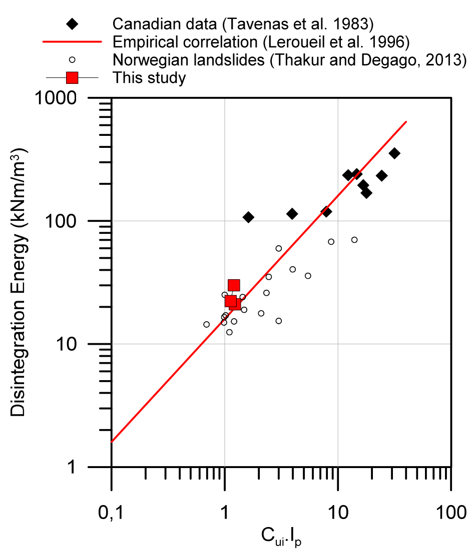

Figure 15 Disintegration energy of the Norwegian and Canadian clays

Based on the laboratory experiments by Tavenas et al. (1983), Leroueil et al. (1996) proposed a pragmatic approach to calculate disintegration energy required for I_r = 100%.

$$W_R = 16\, c_{ui}\, I_p \qquad [6]$$

In addition, Thakur and Degago (2013) proposed an analytical solution to estimate the disintegration energy of Norwegian sensitive clays based on 18 Norwegian landslide sites. The disintegration energy estimated from vane shear results as presented in this study are compared with the results from the previously mentioned studies (Tavenas et al. 1983, Leroueil et al. 1996, Thakur and Degago 2013), see Figure 15. It can be seen that the analytical and the in-situ measurement of the Norwegian sensitive clays are in good agreement. Also the vane shear test data for the Norwegian sensitive clays seems to be in reasonably good agreement with the empirical correlation by Leroueil (2001).

5.2 Some aspects of vane shear testing

Since the inception of the vane shear test method, there has been significance discussion related to the factors that influence the results of vane tests. It is known that the vane installation causes remolding and change in the stresses immediately as well as with time. The effect of vane dimensions, time, the mode of failure in low plastic clays and local pore water pressure drainage must be considered in the analyses. Another important aspect is the strain-rate (rate of radial displacement rotation) of the test. (Skempton 1948; Bjerrum 1972, 1973, Larsson 1980, Aas et al. 1983, Azzouz et al. 1983, Chandler 1988, Mayne and Mitchell 1988; Mesri 1989, Morris and Williams 1993 & 1994; Flate 1966; Gylland et al. 2013). However, it should be realized that in this study an attempt is made to utilize the vane test for an uncommon purpose, namely determination of the disintegration energy. Despite the aforementioned issues, the vane test was capable of providing significant information regarding the disintegration process in sensitive clays. In view of the limitations related to the vane shear tests, the obtained results were satisfactory and valuable; and give important motivation for further research.

6 CONCLUDING REMARKS

This work proposes determination of DE based on stress-vane rotation relationship of sensitive clays obtained using electrical field vane shear tests. This work shows that a representative stress-strain behavior of soft sensitive clays can be established using this method. Despite the limitations associated with the testing procedure, the results are promising. This study shows that the empirical solution proposed by Leroueil (1996) and the analytical solution proposed by Thakur and Degago (2014) are applicable also for Norwegian sensitive clays. However, further efforts should be made to validate the obtained results using extensive field testing for different in-situ conditions.

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