REMOULDING ENERGY AS A CRITERION IN ASSESSING RETROGRESSIVE LANDSLIDES IN SENSITIVE CLAYS: A REVIEW AND ITS APPLICABILITY TO EASTERN CANADA

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ABSTRACT

Sensitive clays are heavily vulnerable to disturbance making them highly susceptible to landslides. The Eastern Canadian region of Quebec and Ontario have large deposits of such sensitive clays which pose a serious threat to life and property. The cause of these land movements and various criteria for assessing their instability are compared and assessed in this review paper based on the remoulding energy and the remoulding index, along with other in-situ and mechanical properties of the soil. The energy distribution within a slope at the time of failure is used to link the remoulding energy to the nature of the material, making it an ideal tool for landslide risk assessment. A comparison of several existing methods for the determination of remoulding energy is made to understand the suitability of each method in future research. The applicability of these methods to Eastern Canadian soils are also verified. The post peak behaviour of sensitive clays and its influence on remoulding energy is analysed and the estimation of remoulding energy through a linear post peak approach is examined. The paper highlights the importance of remoulding energy and its accurate determination through the best fit stress-strain curve to understand retrogressive landslides in sensitive clays.

Keywords: sensitive clays, retrogressive landslides, remoulding energy, strain softening

INTRODUCTION

Sensitive clays underly large areas of the Northern hemisphere including Canada, Sweden, Norway, Finland, Russia, as well as Northwestern regions of America. Their existence is due to isostatic depression and post-glacial rebound followed by the leaching of sea sediments. (Torrance 1983). Clays are considered sensitive when they are susceptible to strain softening. The susceptibility of clays to undergo strength loss is often quantified by the sensitivity index (S_t) which is the ratio of shear strength of the undisturbed soil to that of the remoulded soil (L'Heureux et al. 2014). Highly sensitive clays with very low remoulded shear strength (defined as less than 0.5 kPa and 0.4 kPa in Norway and Sweden respectively) are referred to as quick clays (NGF 2013; Karlsson and Hansbo 1989). In Canada, this is defined based on sensitivity according to the modified fourth edition of the Canadian Foundation Engineering Manual, where clays with sensitivities of 16 or above are termed quick (CGS 2013). A major hazard posed by sensitive clays are the retrogressive landslides, often leading to loss of life and property.

Landslides in sensitive clays have often been described in the past to be initiated from a small shallow circular slide followed by several slides leading to a large retrogressive landslide (Eden 1970; Bjerrum 1955) or due to displacements within a clay mass along a nearly horizontal failure surface (Odenstad 1951; Carson 1977; Locat et al. 2011). However, years of rigorous research on landslides in sensitive clays by researchers has yielded a wider perspective of landslide types and mechanisms (Locat et al. 2011; Quinn et al. 2011). Some examples of landslides in sensitive clays of Quebec include retrogressive slope failures that occurred at Saint Jean Vianney in 1971 (Tavenas et al., 1971), St. Jude in 2010 (Locat et al., 2017) and Saint-Luc-de-Vincennes in 2016 (Tremblay-Auger et al., 2021).

The retrogressive nature of landslides in sensitive clays has led to the analysis of these clays from the point of view of post failure movements and remoulding process. Remoulding in sensitive clays is the result of continuous strength degradation due to the destruction of its fabric (Skempton and Northey, 1952). The strain energy required for remoulding is termed the "remoulding energy". It is also referred to as the "disintegration energy", "degradation energy" or simply "strain energy" (Leroueil et al., 1996; Tavenas et al., 1983; Thakur and Degago 2013). An accurate depiction of the complete stress-strain behavior in the post-peak regime is essential in its estimation. There are several criteria in the analysis of retrogression in sensitive clays. As opposed to these isolated criteria based on only individual parameters such as slope geometry (Mitchell and Markell 1974), physical properties like liquidity index (Lebius et al.

1983), liquid limit (Tavenas et al. 1983) or remoulded shear strength (Leroueil et al. 1983; Locat and Demers 1988), mechanical properties like brittleness index for sensitive clays (Quinn et al. 2011) or quickness (Thakur and Degago 2012), remoulding energy and remoulding index encompass the effect of several parameters together. It takes into consideration undrained shear strength, brittleness as well as slope geometry in its estimation. The importance of representing strength degradation during slope failures in terms of remoulding index is also highlighted by Kennedy et al. (2021) and Potvin et al. (2022) as evidences suggest that the undrained shear strength at the end of retrogression may not always correspond to the completely remoulded shear strength. The objective of this review paper is to present remoulding energy and remoulding index as important criteria in the analysis of retrogressive landslides along with other physical and mechanical properties of the clay. Firstly, the mechanism of landslides in sensitive clays of Eastern Canada are thoroughly examined to get insights to establish a criterion for landslide assessment. Subsequently, the study highlighted the concept of remoulding energy and explored various methods to quantify it. Following that, a parametric study is conducted to investigate the relationships between remoulding energy and geotechnical properties such as liquidity index, plasticity index and preconsolidation pressure. Finally, this review paper concluded with a comprehensive analysis and discussion on future quantification of remoulding energy for sensitive clays of Eastern Canada.

MECHANISM OF LANDSLIDES IN SENSITIVE CLAYS

Most of the landslides of Eastern Canada seem to take place during the wet times of the year (mostly spring) indicating the important role played by water (Eden 1970). It has been often reported that infiltration due to rain or snow or the presence of a nearby water course can be one of the major reasons that trigger retrogressive landslides in sensitive clays. Sensitive clay layers are often found to occur in nature as sandwiched between an upper dry crust and a lower till layer or fissured bed rock (Lafleur and Lefebvre 1980). Sensitive clay slopes of today have emerged over years of fluvial erosion where the rivers cut through these clay deposits to form valleys. As erosion by rivers or streams through the marine deposits and the subsequent valley formation progress over time, a critical position is reached wherein the pore water pressure tries to flow upwards but is restricted due to the relatively lower permeability of the clay layer. This leads to a high pore water pressure at a relatively low overburden stress and a subsequent reduction in effective stress. This can give rise to a low shear strength in the slope that can lead to large flowslides and subsequent retrogression (Lafleur and Lefebvre 1980; Lefebvre 1996). Examples of similar cases include the Saint Jean Vianney landslide of 1971 where partial flooding due to surface runoff was experienced about 3-4 days before the occurrence of the landslide (Tavenas et al. 1971). Investigations of the 1994 St Monique landslide attributed the presence of high porewater pressure and upward seepage conditions to the presence of the Nicolet River, only 650 m west to the landslide site (Locat et al. 2014). Piezocone measurements on the more recent St. Jude landslide that occurred in 2010 indicated upward seepage near the toe of the slope with high artesian pressures (Locat et al. 2017). Although 10% of the landslides take place due to human activities like excavations at the toe of the slope, blasting, overloading the crest of the slope by fill work and pile driving, the remaining 90% are all caused by natural mechanisms as the majority of these slopes have their origin near the banks of water courses which constantly cut into the marine deposits at the toe of the slope (Demers et al. 2014).

According to the Varnes classification of landslide types and their update by Hungr et al., (2014), the majority of retrogressive landslides in Quebec can be classified as flow slides or lateral spreads. The failure mechanism of flowslides is quite clear and well narrated in the literature (Bjerrum 1955; Tavenas et al. 1983). As illustrated in Figure I, in a retrogressive flowslide, an initial rotational failure surface causes the soil to flow and slide out of the crater, leaving an unstable backscarp. An unstable backscarp in this context maybe referred to a condition where the soil undergoes significant loss of shear strength and moves out of the crater leaving behind a high slope that may not be relied upon as a counterbalance to support the remaining slope (Bjerrum 1955; Tavenas et al. 1983). This will cause the occurrence of another failure surface where more soil slides and flows out of the initial crater. This cycle is repeated with multiple failure surfaces until a stable backscarp is formed. An interesting physical model using a geotechnical centrifuge has been shown by Kennedy et al. (2021) which models this exact behavior. In the field, the remoulded clay completely flows out of the crater and can travel long distances depending on its potential energy as well as the geological conditions of the site (Hungr et al., 2014; Locat et al., 2011).

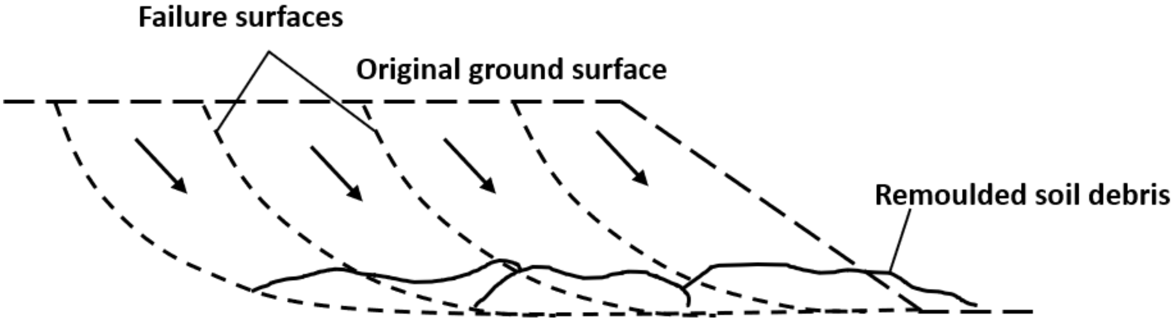


Fig. I Mechanism of flowslides with rotational failure surfaces (adapted from Locat et al., 2011)

Lateral spreads on the other hand are characterized by a ribbed appearance of pointed soil structures (horsts) and flat-topped strips of land with the vegetation more or less intact (grabens) as shown in Figure II. In a spread, failure occurs as a result of the propagation of a sub-horizontal failure surface, more specifically called a shear band/shear zone which develops near the toe of the slope dislocating the soil mass above the shear band into horsts and grabens that subsides in the underlying remoulded soil debris (Hungr et al., 2014; Locat et al., 2011). It is observed that there are cases where a combination of the two mechanisms of flow slides and spreads also occur. Initially, the flow slide may occur leaving behind an unstable backscarp, creating conditions for a spread to occur. The resulting landslide will have characteristics of both a flow slide and a spread (Demers et al., 2014; Locat et al., 2017; Tremblay-Auger et al., 2021). Sometimes a retrogressive slip follows an episodic nature where multiple slip surfaces are formed over years rather than a single event like the Mud Creek landsldie in Ottawa (Potvin et al. 2022).

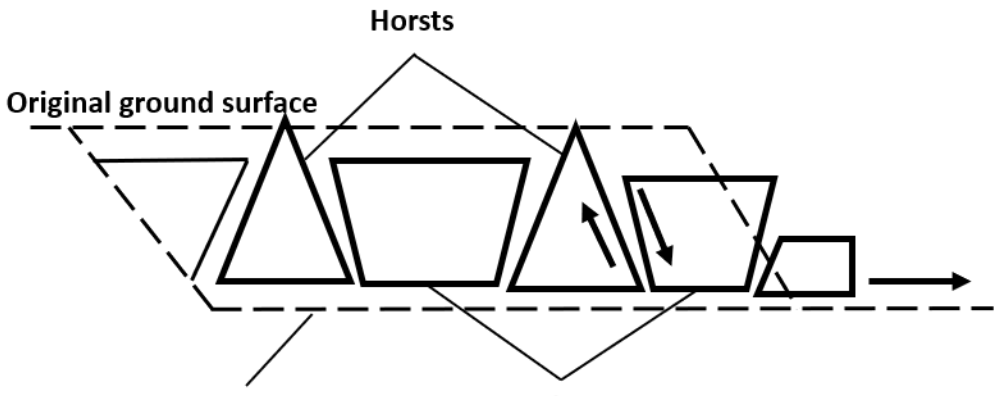


Fig. II Mechanism of spreads in which the failure surface is almost horizontal forming horsts and grabens (adapted from Locat et al., 2011)

Flow slides are more retrogressive in nature than spreads as the remoulded soil debris flows from the point of occurrence of the landslide (Demers et al. 2014). Often times this results in the soil debris resembling a bottle neck shape (Locat et al. 2011). The distinctive horsts and graben formation in a spread failure make them stand out from flowslides. The mechanism of the formation of horsts and graben dates back to the finding of Odenstad (1951) from the Sköttorp landslide in western Sweden that underwent a translatory motion. Later, several studies on the mechanism of spread failures led to the idea of a lateral spreading of a failure surface progressing upwards leading to a horst and graben formation with the remoulded soil being squeezed out due to tension cracks between the horsts and grabens (Mollard and Hughes 1973; Odenstad 1957; Carson 1977). In recent times, a progressive failure analysis related to large landslides in sensitive clay has been proposed, wherein the complete failure surface is formed prior to a slope's subsidence and the propagation of a shear band takes place along this failure surface (Bernander 2000; Locat et al., 2011; Quinn et al. 2011). As the shear band propagates, the shear stress along the failure surface at each point increases to the peak shear strength and then drops to the residual strength. The propagation of shear band ultimately leads to the global failure of the slope when horizontal forces reach active or passive failure conditions (Locat et al. 2011). A small disturbance, in the form of erosion or human activity, can trigger the subsidence and the movement of the slope creating the effect of an apparent retrogression (Quinn et al. 2007).

The realization of these land movements is often difficult due to the complex flow behavior, accurate interpretation of post failure movements and strength loss at large deformations. However, computational techniques and numerical modelling efforts to analyse these behaviors have been evolving over the past decade especially for spread failures. Advanced modelling techniques such as BIFURC, MPM (Material Point Method), LDFEM (Large deformation finite element modelling) and SPH (Smoothed Particle Hydrodynamics) (Locat et al. 2013; Tran and Solowski 2019; Shan et al. 2021; Lian et al. 2023) have been successful in generating accurate landslide mechanisms and post-failure movements in Eastern Canada and Norway. The recent work by Lian et al. (2023) using a fully coupled hydromechanical approach was also able to capture the development of excess pore water pressure during retrogressive flowslides, attributed to the change in permeability under large deformations. The various modelling techniques highlight the influences of sensitivity, remoulded shear strength, slope geometry, brittleness and large deformation strains in characterizing these movements.

EXISTING CRITERIA FOR RETROGRESSION IN SENSITIVE CLAYS

Early studies on strength loss and failure bring to light certain mechanical properties such as the brittleness index (I_B), remoulding energy (E_R) and remoulding index (I_r) which characterize strength degradation and remoulding behavior of soils. The inherent properties of a soil including shear strength, stability number (N_c) and quickness (Q) also play important roles in assessing retrogression. These definitions are briefly summarized in the following paragraphs.

Bishop (1971) introduced I_B to characterize strength loss under drained conditions from the peak to the residual shear strength while using the conventional methods of slope stability analysis for progressive failures:

$$I_B = \frac{\tau_p - \tau_r}{\tau_p} \tag{1}$$

where, τ_p = peak shear strength, τ_r = residual shear strength. According to Quinn et al. (2011)'s concept of progressive failure, the rupture surface/weak layer is already formed over years of strength degradation and essentially is a drained phenomenon. Through a fracture mechanics analysis, they claim that the strain or displacement along the shear band is an equally important factor in comparison to the "residual" strength in the assessment of brittleness. As Bishop (1971)'s equation for I_B fails to represent this, Quinn et al. (2011) put forth a new brittleness parameter for sensitive clays (B_{St}) in terms of nominal deformation localized in the shear band, which at any given time is a fraction of the large deformation. This incorporates strain softening behavior of sensitive clays as well (Equation 2). B_{st} represents the ease in which strength loss is achieved from the peak to the remoulded shear strength and is essentially different from the original brittleness parameter developed by Bishop (1971). For sensitive clays, B_{St} is nearly equal to one.

$$B_{S_t} = \frac{1}{125\bar{\delta}} \tag{2}$$

where $\bar{\delta}$ is the nominal deformation of the shear band.

One may think sensitivity to be a relevant parameter in the assessment of retrogression, however, there appears to be no direct relationship between sensitivity and retrogression distance (Mitchell and Markell 1974). Carson (1977) proposed that rather than the exact ratio of strength loss from peak to residual, the ease with which this strength loss is achieved is more relevant in assessing retrogression.

N_c is a dimensionless parameter used to evaluate the slope stability of cohesive soils and is defined as $\gamma H/c_u$ where γ is the unit weight of the soil, H is the height of the slope and c_u is the undrained shear strength of the intact soil. Mitchell and Markell (1974) found that when N_c was more than 6, plastic flow was likely to occur causing flow slides in sensitive clays. They also observed that the retrogression distance increased parabolically with increasing N_c. However, Demers et al (2014) later suggested that Mitchell and Markell (1974)'s relation showed a scatter in the case of landslides in Quebec and were invalid. Kennedy et al. (2021) explains this due to the non-inclusion of additional constraints in the form of slope angle, shear strength at the end of retrogression, geomorphology of the sites and treating flow slides and spreads separately, which would give rise to more refined correlations for retrogression.

Preliminary investigations in the field of retrogressive slides in sensitive clays by Tavenas et al. (1983) show that the remoulding index and the remoulding energy can provide important information on the behaviour of remoulded soils. Remoulding energy signifies the strain energy stored in a clay material to completely disintegrate its structure into a semi fluid state and the extent of remoulding is indicated by the remoulding index. According to Tavenas et al. (1983), for retrogression to happen in a flowslide two conditions must be met – the initial slide should leave an unstable backscarp and the clay must be remoulded enough to flow out of the crater. They introduced a normalized remoulding energy (E_N) by normalizing remoulding energy by the limit state energy which is the energy involved in reaching the peak strength condition in a soil specimen. Subsequently, Tavenas et al. (1983) defined remoulding index as follows:

$$I_r = \frac{c_u - c_{ux}}{c_u - c_{ur}} * 100 \tag{3}$$

where, c_u = undrained shear strength of undisturbed specimen, c_{ux} = shear strength of partly remoulded clay and c_{ur} = undrained shear strength of remoulded soil. They further proposed that $I_r > 70\%$ and $E_N < 40$ were required for heavy retrogression to take place.

Lebuis et al. (1983), from their observations of Champlain Sea deposits, proposed that clays with liquidity index (I_L) > 1.2 could remould and undergo retrogressive landslides of more than 100 m in distance. Certain correlations between remoulded shear strength (c_{ur}) and liquidity index (I_L) were also proposed by Leroueil et al. (1983) and Locat and Demers (1988) for Eastern Canadian clays. These include $c_{ur} = (I_L - 0.21)^{-2}$ by Leroueil et al. (1983) and $c_{ur} = (335.87/I_L)^{2.44}$ by Locat and Demers (1988) where c_{ur} is in kPa. These equations correspond to c_{ur} as low as 1 kPa at I_L = 1.2. However, Tavenas et al. (1983) provided contradictory evidences to Lebuis et al. (1983) criterion ($I_L > 1.2$) by proposing that heavy retrogression in certain slopes in Eastern Canada were not observed even when I_L was more than 1.2. They also proposed that when liquid limit (ω_L) was less than 40%, heavy retrogression could be observed for Eastern Canadian sensitive clays. Tavenas et al. (1983) explained this as the loss of interparticle bonding among clay particles at $\omega_L < 40\%$, making the clay very brittle and easily remouldable. Researches also show that low Atterberg limit values are typical of sensitive clays owing to their reduced salt content due to leaching (Bjerrum 1955; Lefebvre 1981; Giles 2020).

Thakur et al. (2013b) proposed a quickness test to evaluate the potential of a sensitive clay to undergo flow sliding by assessing the slump of a sensitive clay sample formed upon lifting a cylinder filled with remoulded clay as shown in Figure III. According to Thakur et al. (2013b), quickness is defined as the ratio of the difference in height of the cylinder and the slumped remoulded clay to the height of the cylinder, i.e. $Q = (H_o - H_f)/H_o$. In the case of Norwegian quick clays, quickness (Q) has been related to c_{ur} as $Q = 15c_{ur}^{-0.7}$. Thakur et al. (2013b) further observed that when $c_{ur} < 1$ kPa and $Q > 15\%$, flow slides and retrogressions were likely to occur.

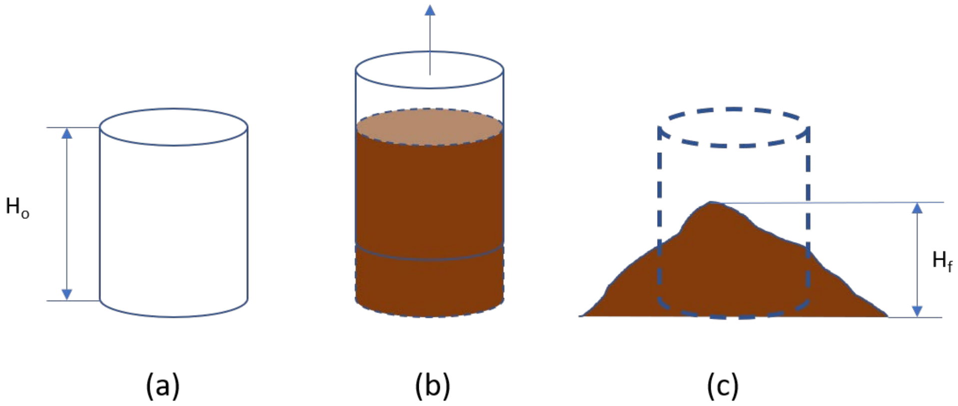


Fig. III Illustration of quickness test: (a) empty cylinder into which clay is poured (b) cylinder is slowly lifted upwards (c) remoulded clay slumps (adapted from Thakur et al., 2013b)

Post-failure movements in sensitive clays or the extent of retrogression maybe assessed in terms of two parameters – retrogression distance and run out distance, measured respectively from crest to crest and toe to toe of the initial and retrogressed slide. Empirical relations to measure these parameters have come into picture in terms of stability number (Mitchell and Markell 1974), volume of soil debris (Locat et al. 2008) and remoulding energy (Thakur and Degago 2013). Certain statistical methods have also been used in Norway which were applied to landslides in Quebec by Turmel et al. (2018) but were found not to predict worst case scenarios. The use of these indirect methods do not always yield accurate results as these encompass only one or two parameters whereas retrogression could be aided/obstructed by several geological factors such as watercourses, presence of valley, depth of slope and etc (Geertsema and L'Heureux 2014). Assessment of remoulding through cone penetration test results of Mud Creek landslide in Ottawa by Potvin et al. (2022) indicated that the soil debris that retrogressed suffered only 50% remoulding. Similar findings were observed by Kennedy et al. (2021) through a physical model of retrogression where a strength degradation of 56 to 80% was observed at the end of retrogression. Thus, the degree of remoulding seems to strongly influence the extent of retrogression and further energy-based studies are warranted.

REMOULDING ENERGY AS A PARAMETER FOR RETROGRESSIVE LANDSLIDES

Energy balance in post-failure slope movements

A slope failure occurs typically in four stages: 1) a pre-failure stage where the soil is intact and possesses sufficient undrained shear strength, 2) a failure stage when the initial slide or shear band propagates depending on the failure mechanism, 3) a post-failure stage when the soil remoulds and undergoes retrogression, and possibly 4) a reactivation stage where the slope slides over a pre-existing failure surface (Leroueil et al. 1996). The post-failure stage where most of the retrogression happens is an important stage in hazard and risk assessment and its behaviour depends on the energy distribution at the failure stage.

Tavenas et al. (1983) suggested that the only source of energy available for remoulding a clay is the potential energy of the sliding mass. The distribution of this potential energy into remoulding energy coupled with the nature of the material determines the extent of retrogression in sensitive clays. During the occurrence of a landslide, just before the failure, the external and the resisting forces of the slope are in equilibrium and the slope has a certain potential energy. According to Tavenas et al. (1983), as the failure progresses, the soil mass moves and the potential energy (E_P) is distributed into a remoulding energy (E_R), a kinetic energy (E_K) and a frictional energy (E_F) according to Figure IV. The remoulding energy determines the amount of remoulding and disintegration that the soil mass undergoes whereas the kinetic energy accelerates the soil debris and the frictional energy controls the movement of the soil mass along the failure surface (Leroueil et al., 1996; Vaunat and Leroueil 2002). The total potential energy is the summation of the above energy components as below:

$$E_P = E_R + E_K + E_F \tag{4}$$

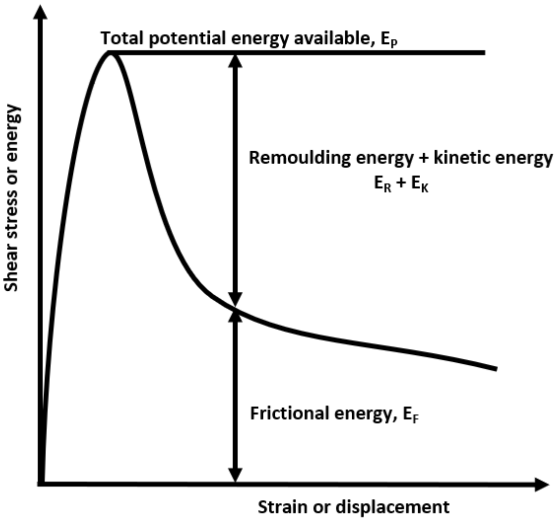


Fig. IV Distribution of post-failure potential energy (adapted from Leroueil et al., 1996)

The distribution of potential energy into the three different forms mentioned above depends on the material type. For a purely ductile material as illustrated in Figure V-a, the potential energy is entirely spent as frictional energy and soil movement is very small. However, for a very brittle material (Figure V-b) the kinetic and the remoulding energies are very high indicating heavy remoulding and retrogression (Leroueil et al. 1996). Since sensitive clays are brittle materials, the latter energy distribution represents their behaviour. The frictional energy of quick clays is often too small or negligible due to their high brittleness.

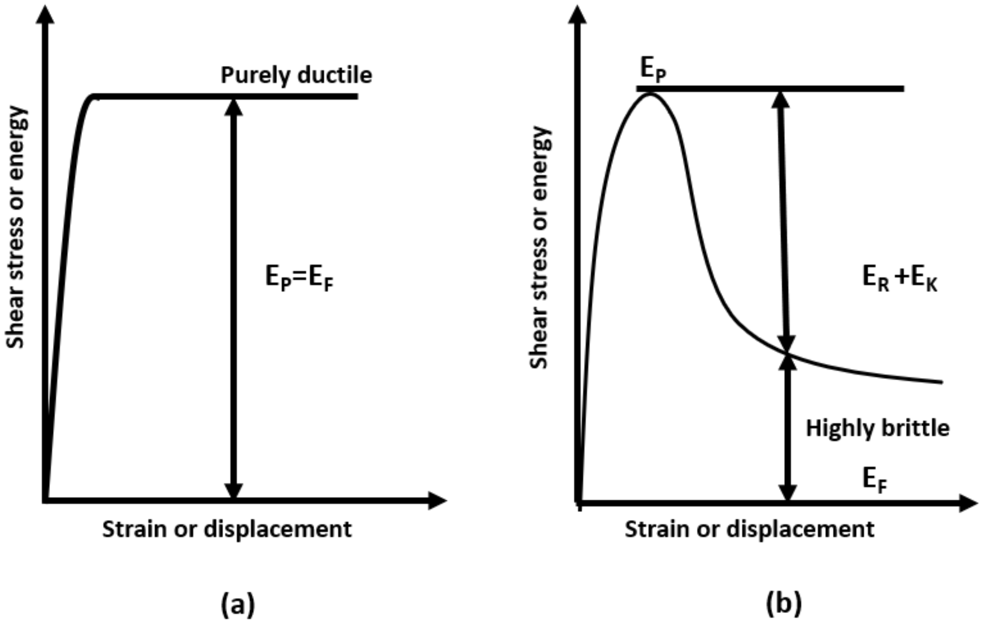


Fig. V Energy distribution for (a) purely ductile material and (b) highly brittle material

Thakur and Degago (2013) proposed the distribution of available potential energy for sensitive clays as follows:

$$E_P = E_R + E_{KF} \tag{5}$$

where, E_{KF} is energy involved in a slide movement i.e., kinetic + frictional energies. Since the total potential energy available at the time of failure is constant, a slope with a lower remoulding energy and higher kinetic energy can be easily remoulded and the remoulded debris can travel larger distances. Quinn et al. (2011) also suggested that large retrogressive landslides occur at a higher remoulding index and a lower remoulding energy.

Existing methods for determining remoulding energy

Tavenas et al. (1983) were one of the forerunners that suggested the use of remoulding energy for characterizing the flow slide potential and the speed at which a clay remoulds using four techniques based on seven samples of Eastern Canadian sensitive clays (Figure VI) as summarized below:

a) Free fall of a cylindrical specimen placed on an inclined board from various heights on a rigid surface.

b) Impact from an aluminum ram, from various heights, on a cylindrical specimen placed on a rigid block.

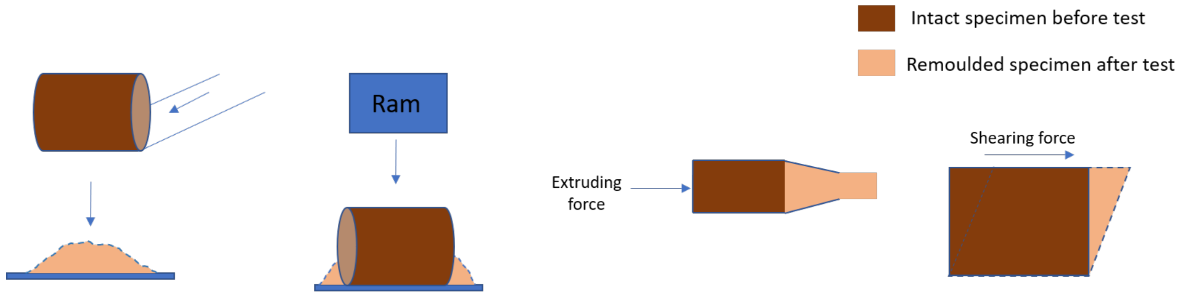
c) Extrusion of soil through a cylindrical mould with a conical opening of various diameters.

d) Shearing in a simple shear box.

Tavenas et al. (1983) worked out the remoulding energy in each of the above scenarios as the energy required to remould the sample at the end of each test. Certain assessments were also made by evaluating the size and the shape of the specimen after each test. Furthermore, they used the Swedish fall cone test to measure the undrained shear strength of the remoulded sample after each test. The process of remoulding starts once the soil exceeds its peak shear strength. Hence, the energy obtained through experimental investigation was divided by the strain energy at the limit state or the peak stress which was assumed as 0.013σ'_p for Champlain Sea clays according to Tavenas et al. (1979). Thus, the normalized energy per unit volume (E_N) maybe written as:

$$E_N = \frac{Energy\ per\ unit\ volume}{0.013\ \sigma'_p} \tag{6}$$

For each of the test scenarios shown in Figure VI, Tavenas et al. (1983) plotted E_N versus I_r. It was observed that for the same remoulding energy, different samples exhibited different remoulding indices indicating that the degree of remoulding undergone by each sample, even at the same remoulding energy, was different depending upon their physical properties which most likely represents their depositional characteristics and minerology.



(a) (b) (c) (d)

Fig. VI Experimental investigations of remoulding by Tavenas et al., (1983) (a) Free fall test, (b) Impact test, (c) Extrusion test, and (d) Shearing test (adapted from Thakur et al. 2013a)

The fundamental experimental data by Tavenas et al. (1983) were later incorporated to develop empirical relationships to determine remoulding energy. Leroueil et al. (1996) showed that the remoulding energy was directly proportional to the in-situ undrained shear strength (c_u) and plasticity index (I_P). They proposed the following empirical equation for remoulding energy, $E_R = 12.5c_uI_P$ at a remoulding index of 75%. Another empirical equation was proposed by Locat, (2008) where $I_R = 14.9(E_R/c_uI_P)^{0.69}$. For complete remoulding (I_R = 100%), $E_R = 16c_uI_P$ is obtained from this correlation.

An analytical approach was developed by Thakur and Degago (2013) for determining the remoulding energy as the area under a simplified stress-strain curve with linear post-peak strength behaviour.

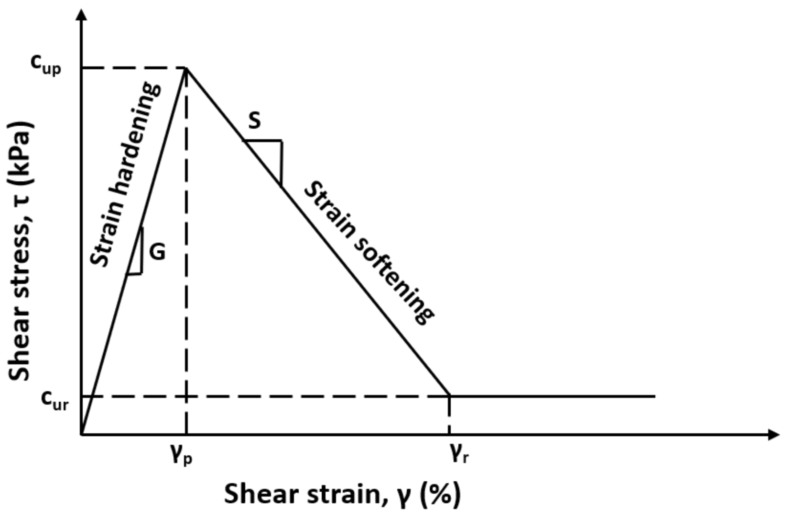


Fig. VII Ideal shear stress - shear strain curve used to calculate remoulding energy (adapted from Thakur and Degago 2013)

The following equation was subsequently proposed by Thakur and Degago (2013) for calculating the remoulding energy (E_R) based on the simplified stress-strain curve of Figure VII:

$$E_R = c_{ur}\gamma_r + \frac{1}{2}(S_t\, c_{ur})^2\left(\frac{1}{G} + \frac{1}{S}\right) \tag{7}$$

where, γ_r = residual/remoulded strain, G = secant shear modulus, S = softening modulus (i.e., slope of the strain-softening segment of the stress-strain curve).

Later, Thakur and Gylland (2015) used the electric field vane shear test (EFVST) to measure remoulding energy for Norwegian clays at a strain rate of 0.2° per minute, where shear strength measurements were carried out from the total corrected torque (T_{tot}) until the vane completed a rotation of 360°. The remoulded shear strength was measured after 25 revolutions of the vane. Based on the results of EFVST, Thakur and Gylland (2015) observed that the shear resistance after a vane rotation (θ) of 90° remained more-or-less unchanged and they reported it as due to the drainage of excess pore water pressure which was considered to be a limitation of the experiment. Thus, remoulding energy was calculated by linear extrapolation of the curve beyond a vane rotation of 90° (Figure VIII). Despite its limitations, the remoulded energy obtained from an EFVST test is found to be consistent with those reported by Leroueil et al. (1996) and Thakur and Degago (2013).

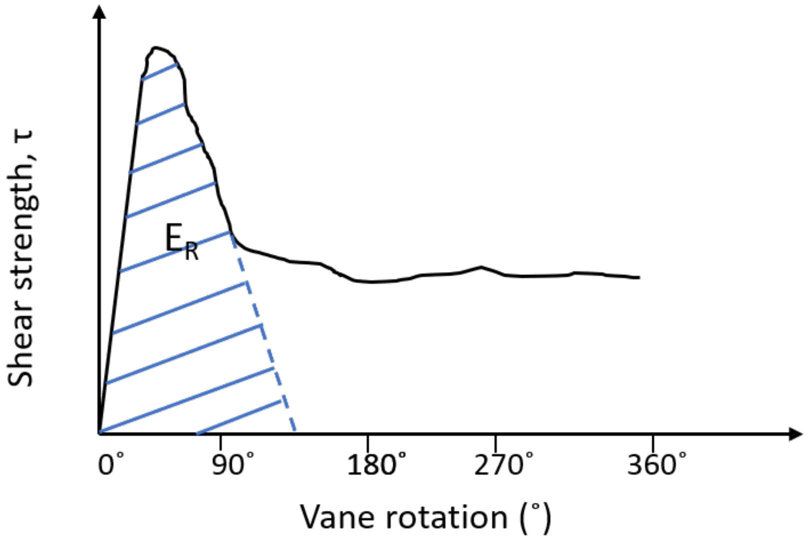


Fig. VIII Shear stress - rotation curve according to Thakur and Gylland, (2015)

DETERMINATION OF REMOULDING ENERGY FOR SENSITIVE CLAYS OF EASTERN CANADA

A preliminary study was conducted to assess the application of existing methods to determine the remoulding energy of Eastern Canadian sensitive clays, particularly the linear approximation proposed by Thakur and Degago (2013). This study has been carried out based on the information obtained from 12 Eastern Canadian sensitive clay sites as given in Table I. The data represent soil characteristics at a particular depth. Undrained shear strength values were obtained through standard field vane tests (FVT).

Table I Properties of Eastern Canadian sensitive clays

Site	Sample depth (m)	I_P (%)	I_L	$c_{u\ (FVT)}$ (kPa)	$c_{ur\ (FVT)}$ (kPa)	S_t	Source
Saint – Leon	4.8	45	1.1	30	1.1	27	Tavenas et al. (1983)
Louiseville	6	45	1.1	39	1.3	30	Tavenas et al. (1983)
Saint - Hilaire	5.6	35	2.3	35	0.8	44	Tavenas et al. (1983)
Saint – Thuribe	6	20	1.6	55	0.4	137	Tavenas et al. (1983)
Mascouche	9	30	1.2	135	1.3	104	Tavenas et al. (1983)
Saint – Alban	6.6	19	2.4	21	0.2	105	Tavenas et al. (1983)
Saint – Jean Vianney	30	13	1.1	320	1.2	260	Tavenas et al. (1983)
Saint Monique	13.45	35	1.25	40	0.7	57	Locat et al. (2014)
Saint Jude	22.1	36	2	47.3	0.3	158	Locat et al. (2017)
James Bay	12	10	2	18	0.09	200	Lefebvre et al. (1988)
Casselman	22.39	10	1.1	85	1.5	57	Durand (2016)
Saint Barnabé	23.31	10	2	77	1.8	43	Locat (2007)

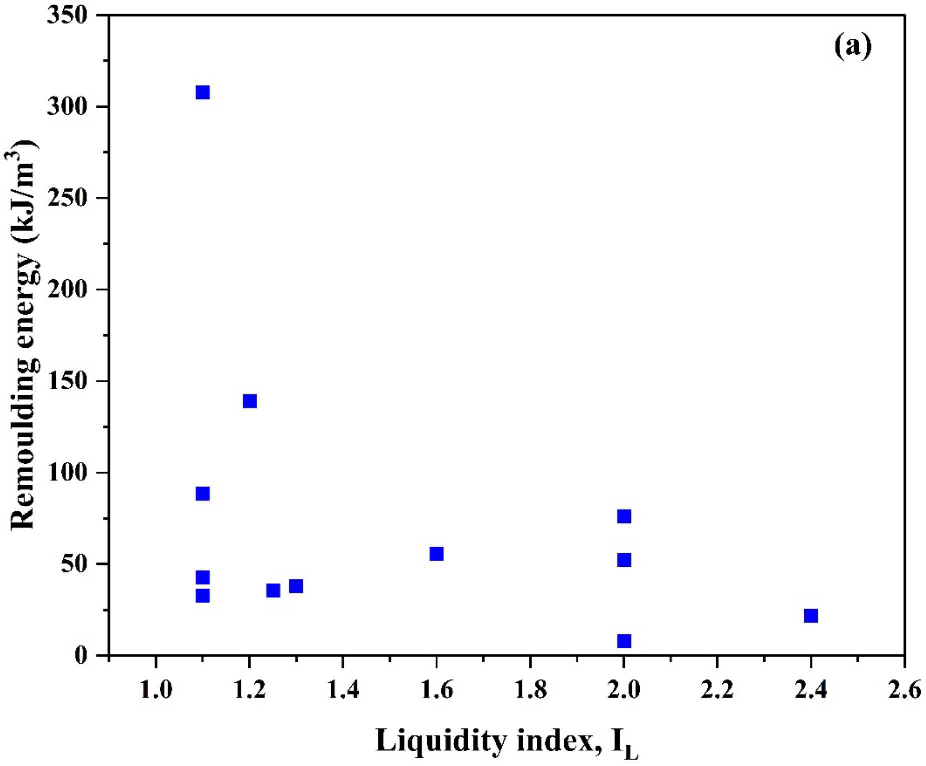
Table II Properties of Norwegian sensitive clays from Thakur and Degago (2013)

Site	I_P (%)	I_L	$c_{u\,(FVT)}$ (kPa)	S_t
Leistad	6	1.5	16.5	110
Hekseberg	4	2.4	25	100
Vibstad	17	0.2	32	8
Borgen	20	1.2	70	100
Lyngen	12	1.5	17.5	50
Byneset	4.8	3.8	14.4	120
Kattmarka	8	2.9	15.12	63
Fredrikstad	20	1	15	30
Rissa	6	2.2	24	100
Baastad	8	1.8	18.55	35
Selnes	7	2.3	35	100
Skjelstadmarka	10	1.6	39.84	48
Furre	6	1.3	17	85
Drammen	11	1.1	10	4
Lodalen	17.1	0.8	51	3
Bekkelaget	9	2.4	26	130
Ullensaker	6.7	1.9	14.7	42
Verdalen	5	2.2	60	300

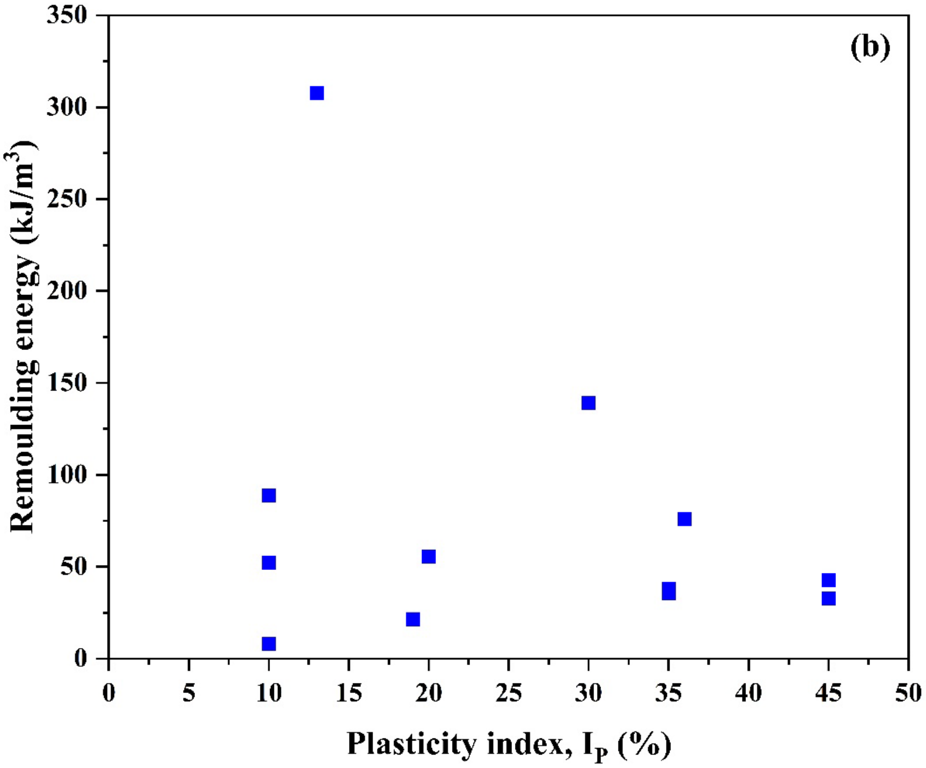
The remoulding energy is calculated using Equation 7 which fits a linear segment to the post-peak stress-strain behaviour of a soil. The equation requires several parameters which are often not readily available from field or laboratory investigations alone and warrants the need of certain assumptions. A critical parameter in this equation is the strain at remoulded strength (γ_r). The accurate determination of γ_r in the laboratory is difficult because of the limited shear strain range of most conventional laboratory strength tests. Hence some of the parameters in Equation (7) were determined through correlations and assumptions based on laboratory and field investigations conducted on Eastern Canadian sensitive clays from various literature (Locat et al. 2014; Locat et al. 2017; Lefebvre et al. 1988; Durand 2016; Locat 2007).

Direct simple shear (DSS) tests conducted on high-quality Eastern Canadian clay samples are sheared up to peak strains of 1 - 5% (Locat et al. 2014; Locat et al. 2017; Lefebvre et al. 1988; Durand 2016; Locat 2007). Based on these laboratory investigations, strain at peak strength (γ_p) and secant shear modulus (G) are assumed to be 4% and $25c_u$, respectively. In order to obtain the strain at remoulded strength (γ_r), the DSS curves were extrapolated by an exponential curve fitting approach up to the remoulded shear strength and an average value of 200% was obtained for Eastern Canadian sensitive clays. Numerical modelling of the post-peak behavior of Eastern Canadian sensitive clays also yielded γ_r = 100 - 200% (Locat et al. 2017; Tran et al. 2019).

The remoulding energy per unit volume estimated from Equation 7 for Eastern Canadian clays is in the range of 20-310 kJ/m^3. The results in Figure IX indicate a certain amount of scatter which primarily resulted from the assumptions made in the estimation of various parameters in Equation 7 as well as the differences in sampling methods – 20 cm in diameter tube sampler in St Leon, Louisville, Saint Hilaire, Saint Thuribe, Mascouche and Saint Alban; 70 mm in diameter thin-walled tube sampler in Saint Monique, Saint Jude, Casselman and Saint Barnabé and block samples in Saint Jean Vianney and James Bay. Similar studies conducted by Thakur and Degago (2013) on Norwegian sensitive clays, yielded remoulding energies per unit volume of 20 - 160 kJ/m^3. Here, the strain at peak shear stress (γ_p), shear modulus (G) and strain at remoulded shear strength (γ_r) were respectively considered as 0.5%, 150 times peak shear stress, and 300% according to previous Norwegian database.


(a)
Remoulding energy (kJ/m³)
0
50
100
150
200
250
300
350
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
Liquidity index, I_L

435


(b)
Remoulding energy (kJ/m³)
0
50
100
150
200
250
300
350
0
5
10
15
20
25
30
35
40
45
50
Plasticity index, I_P (%)

436

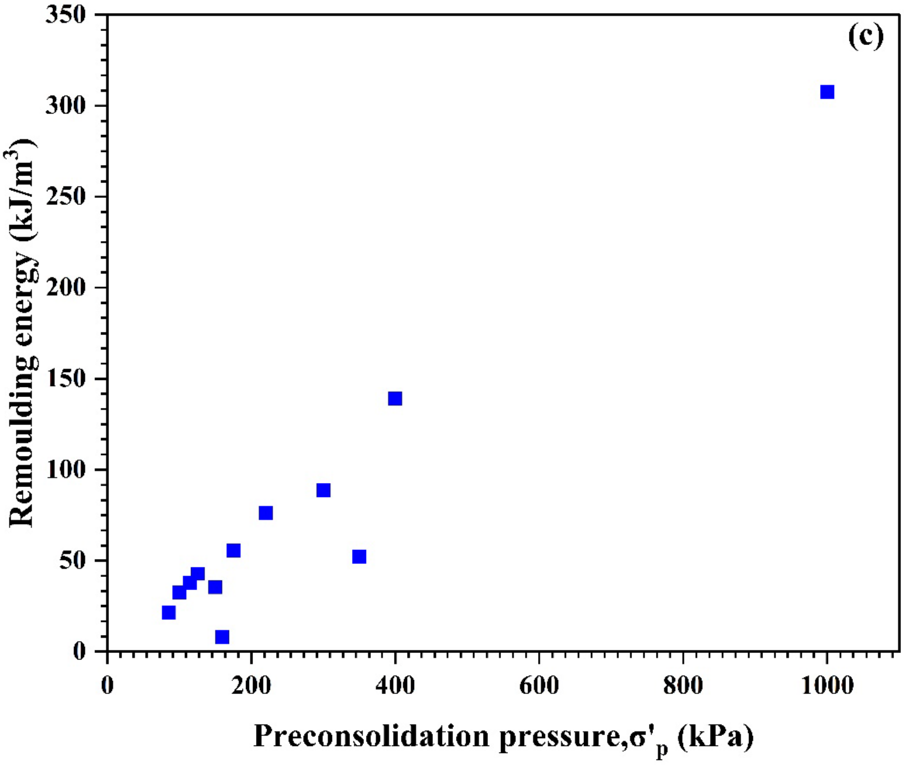
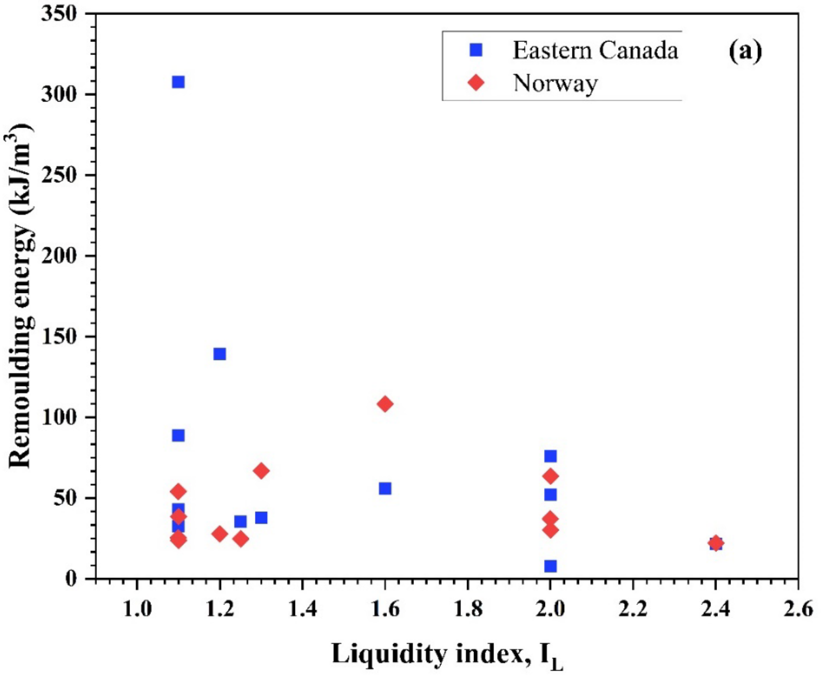


Fig. IX Variations of remoulding energy for Eastern Canadian clays with (a) liquidity index, (b) plasticity index and (c) preconsolidation pressure

The value of remoulding energy primarily depends on the undrained shear strength and the ease of strength degradation or the softening undergone by the soil. Figure IX shows that the remoulding energy has a positive correlation with the preconsolidation pressure (σ'_p) and no correlation with I_L and I_P. This means that the factor that primarily affects remoulding energy is the stress history of the soil and physical parameters have very low to no dependance on the remoulding energy. Figure X compares the remoulding energies of Eastern Canadian (this study) and Norwegian (Thakur and Degago 2013) clays and further shows the poor correlation of physical properties with remoulding energy even for Norwegian clays. On average, remoulding energies of Eastern Canadian and Norwegian clays seem to be more or less in the same range. The Norwegian clay data used for comparison are taken from Thakur and Degago (2013) and are shown in Table II.



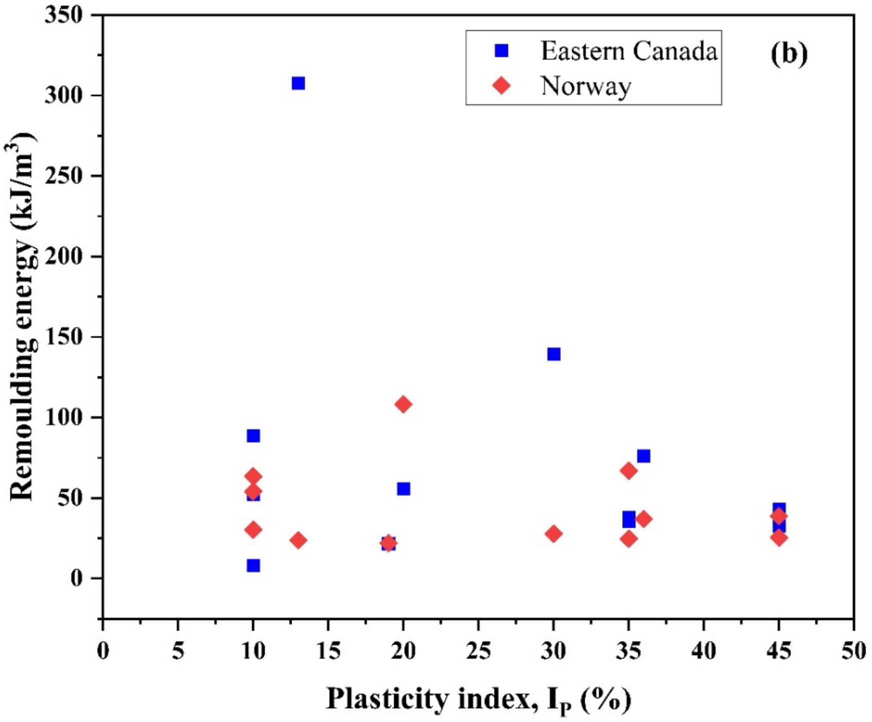


Fig. X Comparison of remoulding energy of Eastern Canadian and Norwegian clays and their dependence on (a) liquidity index and (b) plasticity index

As mentioned earlier, Thakur and Degago (2013) considered a linear post-peak behavior in their estimation of remoulding energy. It is however apparent that the actual post peak behavior is non-linear even though this is quite difficult to portray. Here, an attempt was made to estimate the remoulding energy by an exponential prediction of the non-linear strain softening curve. Data from five of the sites in Table I (Saint Monique, Saint Jude, James Bay, Casselman, Saint Barnabé) were used for this estimation. The DSS test results seem to fit well with an exponential variation and hence this simple extrapolation was carried out to obtain the complete non-linear post-peak behavior curve (Figure XI). In the analysis of post-peak behavior of large retrogressive landslides, it is often noticed that strength degradation at end of retrogression does not always correspond to 100% remoulding in the field (Potvin et al. 2022). Thus, energy at each level of remoulding indicated by the remoulding index, I_r (Equation 3) would be a much better representation. Remoulding energy at each degree of remoulding is presented in Figure XII and these curves are obtained from the stress-strain curves of Figure X1. Due to the brittle nature of sensitive clays, energy degradation close to complete remoulding (taken as 80% in this study) could happen quite soon and the variations are almost linear as shown in Figure XII. As suggested by Potvin et. al. (2022), strength degradations beyond this may not always take place in the field. Also, c_{ur} for these clays is about 1.5 – 0.1 kPa (as reported by the corresponding literatures) and the accurate measurements of such low strengths could also be difficult. Hence the practical effect of remoulding energy corresponding to exactly 100% remoulding should be further analysed with sophisticated numerical computations.

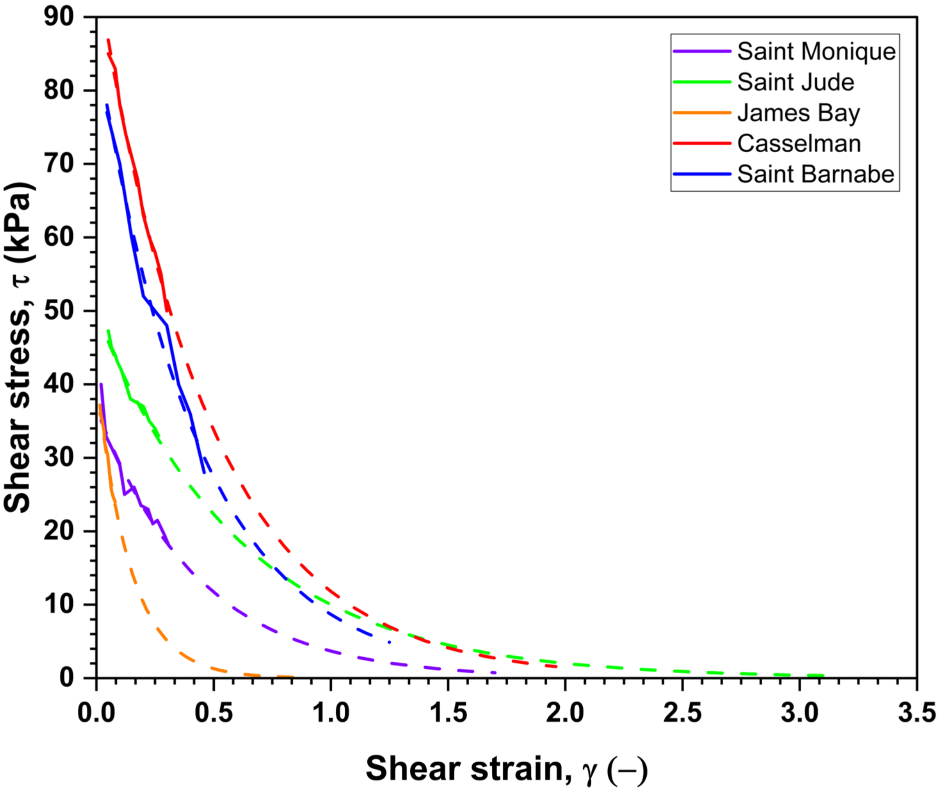


Fig. XI Post-peak strain softening curves from DSS results of selected Eastern Canadian sites (solid lines represent the laboratory data and dashed lines show the exponential extrapolations)

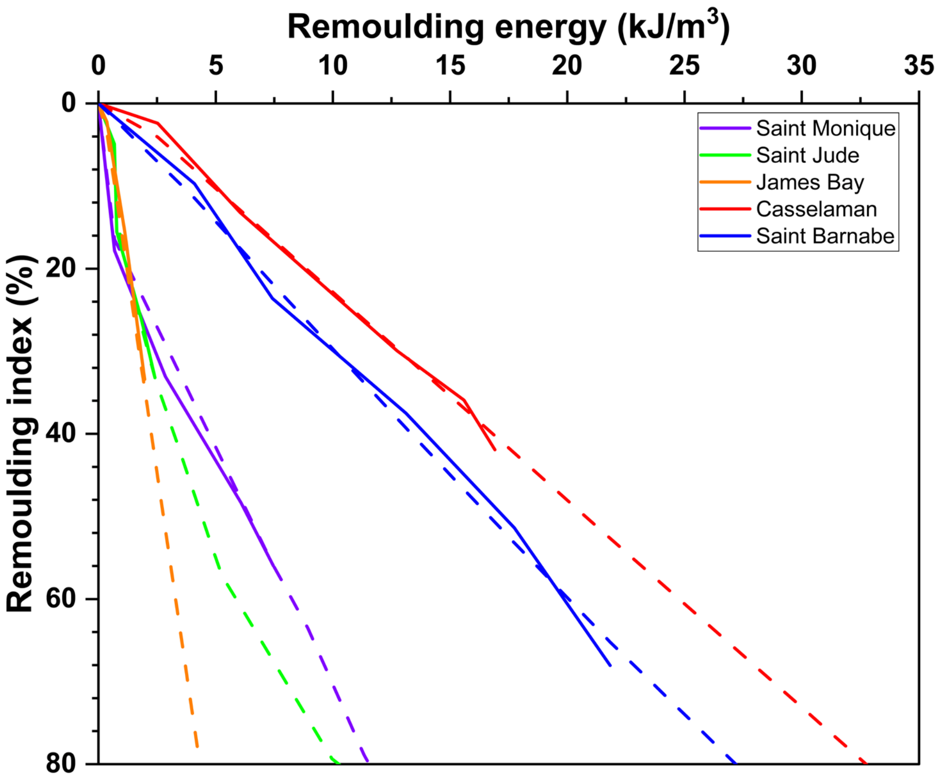


Fig. XII Remoulding energy at various degrees of remoulding index obtained from DSS results (solid lines represent the laboratory data and dashed lines show the exponential extrapolations)

DISCUSSIONS

The occurrence of disastrous landslides in sensitive clay slopes of certain Northern countries, especially in Eastern Canadian region, has been studied extensively over decades in various literature (Tavenas et al. 1983; Locat et al. 2008; Quinn et al. 2011; L'Heureux et al. 2014). Natural processes like erosion or climate change can cause reduction in mean stress and an increase in shear stress under drained loading. These seemingly stable slopes can undergo remoulding through sudden loading in the form of loss of resisting forces (e.g., toe erosion near marine slopes, excavation), increase in driving forces (e.g., construction of embankment) or increase in pore pressure (e.g., heavy rainfall, melting of snow, vibration, rapid loading), followed by retrogressive landslides depending on soil conditions and morphology. In the analysis of retrogressive landslides, the advantage of material properties such as quickness, brittleness index, remoulding index and remoulding energy is that they directly represent the nature of a sensitive clay material, whereas other criteria based on post failure movements are mostly empirical and hence require site specific data. However, since the determination of liquid limit, liquidity index, plasticity index and remoulded shear strength are relatively straightforward and reliable, criteria based on these parameters are widely accepted and used. Retrogression is quantified in terms of retrogression distance and runout distance. Although there are specific soil parameters that affect the amount of retrogression, an energy dissipation approach in the form of remoulding energy seems to accurately encompass strain softening and the severity of strength loss. An empirical relation in this very context has been given by Thakur and Degago (2013) and confirms that a lower remoulding energy is associated with more retrogression.

The linear approximation made by Thakur and Degago (2013) in forming Equation 7 provides a simplified and adequate methodology to determine remoulding energy. However, a clear analysis of the observations made in this paper indicates that it is the post-peak behaviour which impacts the remoulding energy, and the rate of strain softening coupled with strain at residual/remoulded state is a critical parameter in this regard. In this context, the impact of secant shear modulus (G) on the remoulding energy is found to be inconsequential. In Equation 7, keeping all other parameters the same, a change in G (even an increase of 5 times) does not produce any significant changes in remoulding energy. An observation is that, as the peak strength is mobilized at small strains, the area under the stress-strain curve up to the peak strength constitutes a relatively insignificant part of the remoulding energy and as a result variation in secant shear modulus (G) has little effect on the remoulding energy. Furthermore, Figures IX and X predominantly show the poor correlation of remoulding energy with physical properties such as the Atterberg limits and the importance of stress history in the determination of remoulding energy. Past empirical correlations and studies for remoulding energy which show its positive correlation with plasticity index (Leroueil et al. 1996; Locat et al. 2008; Thakur and Degago 2013) should be used with caution as they alone may not provide accurate assessments of remoulding energy. Considerations of post-peak parameters at large deformations and the ease with which this state is arrived at based on a non - linear stress-strain behavior is specifically important for the estimation of remoulding energy. Upon observation of Figures XI and XII it is noticed that the variation of remoulding energy with remoulding index is almost linear and this slope is dependent on the softening of the corresponding stress-strain curves.

Overconsolidated clays under undrained shear exhibit strain-softening behaviour and sometimes with much pronounced strain softening at low confining stresses (Locat et al. 2011;

Lefebvre and La Rochelle1974; Lefebvre et al. 1981). It is well understood that Norwegian sensitive clays are only slightly overconsolidated in comparison to Eastern Canadian sensitive clays (Thakur and Degago 2013; L'Heureux et al. 2014) and hence may exhibit lower brittleness and higher remolding strains in comparison to Eastern Canadian clays. As a result, a linear post peak behaviour may correlate well with the actual non-linear post peak behaviour. However, in the case of Eastern Canadian sensitive clays, a linear approximation overestimates the remoulding energy due to the pronounced strain softening it undergoes at low confining stresses. This could be corrected through experimental investigations on site specific samples and considering the non-linear strain-softening behaviour of sensitive clays. Moreover, material properties like brittleness index could provide better physical dimensions to develop an equation for remoulding energy considering their relevance in the process of remoulding.

Researchers are still struggling to understand the extend of retrogression and the reactivation of landslides in sensitive clays in terms of time. These landslides are very unpredictable as to whether they continue to be active or not. The Saint Jean Vianney landslide in Saguenay in 1971 was said to have started from the crater of a larger landslide which occurred 500 years ago (Tavenas et al. 1971). The Beattie mine in Quebec, where a landslide occurred in 1943, witnessed a shallow slide in 1937 before the occurrence of the landslide and even continued to have large slides until 1946 (Eden 1964). The Mink Creek landslide which occurred in Terrace, British Columbia in 1994 was also not the first movement in this area with two other landslides in 1962 and several prehistoric flowslides in this area (Geertsema et al. 2006). Thus, the susceptibility of an area to disastrous landslides does not end with a single event or even several events over the course of few years. This creates further uncertainty in post-landslide operations including restoration and rehabilitation. These uncertainties may be reduced through detailed soil investigations which can add more precision to the estimation of remoulding energy and the constitutive and numerical models for landslide prediction.

Based on the aforesaid observations, the authors believe that there is limited experimental data after Tavenas' study and there is a need to continue research on the post-peak behaviour of Eastern Canadian sensitive clays with site specific data to determine remoulding energy and its correlations with other post-peak parameters.

CONCLUSIONS AND SUMMARY

This review paper provided a comprehensive overview of different types and failure mechanisms of sensitive clay landslides in Eastern Canadian region and evaluated various criteria for their assessment. Among existing criteria, remoulding energy and remoulding index were found to assess post-failure landslide movements with more precision. However, the expansion of these concepts towards detailed assessment of retrogressive landslides in sensitive clays was found to have received less attention in spite of their potential. Some of the key findings of the present study are as follows:

- Critical evaluation of various studies indicated that post - peak stress - strain behavior of strain-softening soils has significant influence on the accurate quantification of remoulding energy and possibly on post-failure landslide mechanisms.
- In the case of Eastern Canadian clays, the determination of remoulding energy based on a non-linear post-peak stress-strain behavior may reduce inconsistencies shown by existing approaches.
- Preliminary comparison of results highlighted that the remoulding energy of Eastern Canadian and Norwegian quick clays appears to be controlled by stress history instead of physical parameters. Existing studies which indicate otherwise should be used with caution.
- Post-failure movements in retrogressive landslides are significantly dependent on energy dissipation during slope failures which in turn depends on the inherent material behavior (brittle or ductile).
- There is a huge need to accurately determine the non–linear post–peak stress–strain behavior of sensitive clays, reproducing in-situ conditions through experimental studies, considering its significance in assessing post–failure landslide movements, and the authors plan to explore this gap in future research.

DISCLOSURE STATEMENT

The authors declare that there is no conflict of interests.

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