Analytical and numerical assessment of the effect of erosion in sensitive clay landslide: A case study of Saint-Jude Landslide

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ABSTRACT
Erosion is regarded as the triggering factor of the majority of the retrogressive landslides in sensitive clays of eastern Canada. Due to the process of valley formation, the soils on the banks of water bodies of eastern Canada are getting eroded over the decades, and the shear strength of the soils near the valleys reduces. This strength reduction is owing to the change in salinity of these soils during the erosion process by leaching salt from the soil to the water bodies. When the slope is marginally stable, a very small increase in stress can trigger large retrogressive failure in sensitive clays. Saint-Jude Landslide that occurred in Quebec in 2010 can be considered a classic example of a landslide triggered by erosion. This study attempts to evaluate the effect of erosion in initiating the failure in a marginally stable slope. The stability of the slope has been determined with limit equilibrium methods and finite element analysis using strength reduction factor prior to the failure, and it has been demonstrated how small stress increase in a marginally stable can initiate failure.

RÉSUMÉ
L'érosion est considérée comme le facteur déclenchant de la majorité des glissements de terrain régressifs dans les argiles sensibles de l'est du Canada. En raison du processus de formation des vallées, les sols des rives des plans d'eau de l'est du Canada s'érodent au fil des décennies, et la résistance au cisaillement des sols près des vallées diminue. Cette réduction de résistance est due au changement de salinité de ces sols au cours du processus d'érosion par lessivage du sel du sol vers les plans d'eau. Lorsque la pente est marginalement stable, une très faible augmentation de la contrainte peut déclencher une rupture régressive importante dans les argiles sensibles. Le glissement de terrain de Saint-Jude survenu au Québec en 2010 peut être considéré comme un exemple classique de glissement de terrain déclenché par l'érosion. Cette étude tente d'évaluer l'effet de l'érosion dans l'initiation de la rupture dans une pente légèrement stable. La stabilité de la pente a été déterminée avec des méthodes d'équilibre limite et une analyse par éléments finis en utilisant le facteur de réduction de résistance avant la rupture, et il a été démontré comment une petite augmentation de contrainte dans une stabilité marginale peut déclencher une rupture.

1 INTRODUCTION

Landslides in sensitive clays are considered one of the major hazards in the northern countries of the world, especially in Canada and Norway. The impact of landslides is catastrophic to both population and economy. Natural resources Canada (NRCan) has reported that in Canada, the annual damages by landslides are worth $200 to $400 million (NRCan 2019). A total of 778 people have died in the landslide events all over the country from 1771 to 2018, among which 134 fatalities are recorded solely in Québec region due to the glaciomarine sensitive clay failures in the St. Lawrence Lowlands (Blais-Stevens 2019). The devastating aftermath of landslides in sensitive clays intrigued researchers to extensively investigate the triggering factors and mechanism of such landslides, most importantly, the behavior of sensitive clays that leads to the initiation and progress of extremely large landslides under different loading conditions. The post-failure behavior of sensitive clays is attributed to the post-peak strength reduction under shear loading. Sensitive clays generally have high intact shear strength, but the shear strength reduces to a significantly low value (remolded shear strength) when subjected to disturbance and the clay completely loses its intact structure and disintegrates to a liquid-like mass (remolded clay) that can flow. Thus, the soil is referred to as “sensitive” because its strength is sensitive to disturbance. The sensitivity (S_t) of soil is quantified by the ratio between the peak and remolded shear strength. Once the slope failure starts in sensitive clays, the clay layer gets remolded to a liquid form and keeps moving away from its original position. The drag of this liquified soil results in subsequent failures (progressive or retrogressive) until the flow of this liquified clay stops or is unable to initiate another failure. Thus, the extent of the failure of sensitive clay slopes is enormous compared to slope failure in non-sensitive soil. For example, recently in the highly sensitive clays of Norway the Gjerdrum landslide (2020), spanned a flow-off area of 210000 m^2 and additionally affected 90000m^2 by debris flow (Liu et al. 2021).

The development of sensitivity (high intact strength with low remolded shear strength) of the clays is attributed to the depositional features of sensitive clays as well as the ongoing weathering effect on embankment soils. Sensitive clays are believed to be deposited in marine environment depressions left by the Laurentian ice sheet around 14000 to 6000 years ago from the present time (Quigley 1980, Lefebvre 1996, 2017). Due to the exposure to the seawater with high salt concentration, the clays formed a flocculated structure with high undisturbed shear strength. With the deglaciation of the ice sheets over time, the lands which were once depressed by the huge weight of the ice sheets rose above the sea level (iso-static rebound). Due to this uplift of the clay deposition above the seawater, the clays got exposed to freshwater. When the freshwater flows through the soil, the salt concentration within the soil mass reduces due to the leaching out of salt into the freshwater. As a result, even though the clays retain their flocculated structure, they do not have the salt ions that were keeping the structure stable. This structure is called meta-stable, which is highly susceptible to disturbance and leads to very low remolded strength. This is why the vast majority of sensitive clay landslides have occurred along watercourses (Figure 1) with active erosion at the toe of the slopes (Lebuis et al. 1983).

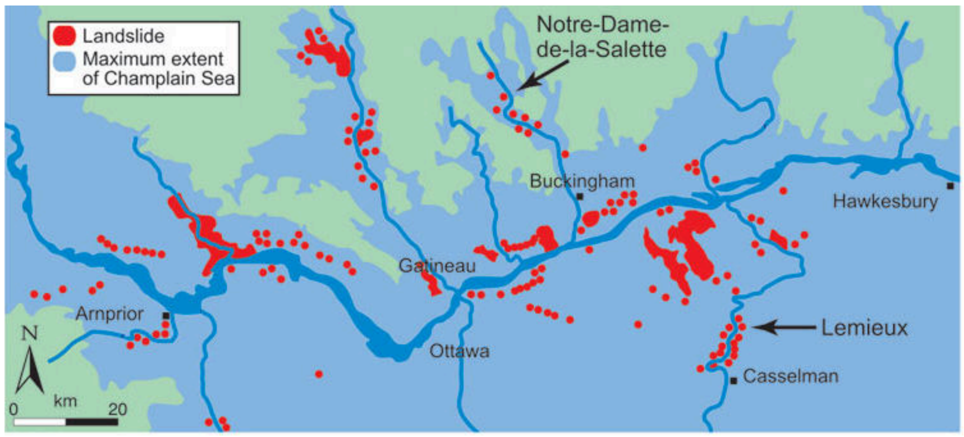

Figure 1. Landslides in sensitive clays in the Champlain sea region (Canadian Geoscience Education Network archive 2019).

Apart from erosion, seismic activity, sudden increase of pore water pressure due to heavy rainfall or melting of snow, or other man-made activities may trigger landslides in a marginally stable slope (marginally stable refers to the factor of safety being slightly over 1). Whatever the final triggering factor for a landslide in sensitive clays is, the pre-failure condition of the slope (marginal stability) is always attributed to the long-term erosion (Lefebvre 1996). That is why It is widely agreed upon that the stability of a sensitive clay slope against the initial slide or the assessment of initial stresses in a sensitive clay slope before retrogressive/progressive failure should be done against drained soil parameters (Bjrum 1955, Michell and Markle 1974, Tavenas et al. 1983, Locat et al. 2013, Lefebvre 2017). Thus, the behavior of sensitive clays in the drained condition is particularly important. While over-consolidated sensitive clays show softening behavior in both drained and undrained conditions (Lefevre 2017), normally consolidated or slightly over-consolidated sensitive clays (Over Consolidation Ratio, OCR < 2) do not show softening behavior in drained condition (Locat et al. 2019) as illustrated in Figure 2. OCR for Norwegian sensitive clays is reported between 1-6 based on 61 samples from 17 different locations among which 12 locations with 39 samples had OCR ≤ 2 (Paniagua et al. 2019). Again Demers et al. 2002 reported OCR values for 31 different locations of Canadian sensitive clays where 17 locations had OCR ≤ 2 and 29 locations had OCR ≤ 5. Therefore, it can be said that a large number of sensitive clay sites are normally consolidated and stability analysis in these sites against long-term erosion does not require the consideration of the drained strain softening. However, once the first slide has taken place, subsequent failures happen within a very short time and retrogression or progression of the failure takes place in undrained condition and large retrogressive failures occur due to undrained strain-softening even though the failure was initiated in drained condition. This information is important in the initial stability analysis of sensitive clay slopes with ongoing erosion in normally/lightly consolidated clays.

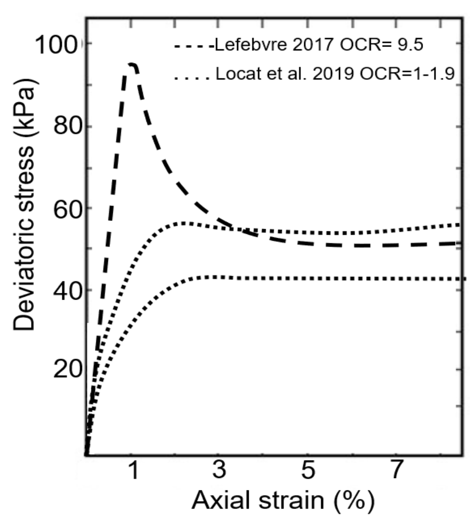

Figure 2. Behavior of sensitive clay under consolidated drained triaxial test

Demers et al. (2014) studied 108 large retrogressive landslides that previously occurred in Quebec and suggested that in 90% of the cases, erosion played an active role in triggering the landslides. Therefore, it is imperative to understand the role of erosion in the instability of sensitive clay slopes for disaster risk mitigation. The objective of this study is to explain the effect of erosion in slope stability analysis in sensitive clay deposits. Firstly, the role of erosion on previously occurred sensitive clay landslides have been presented, and finally a case study of erosion-induced sensitive clay landslide has been investigated analytically and numerically to provide insights on the effect of erosion on the failure initiation of sensitive clay slopes.

2 HISTORY OF LARGE LANDSLIDES ON ERODED MARGINALLY STABLE SLOPES

A detailed record of sensitive clay landslides is available in the literature from the early eighteenth century to the present time. This section discusses the pre-failure conditions of the slopes before the occurrence of large landslides and the contribution of erosion in making the slope susceptible to failure.

Brzezinski (1971) reported that in the Kenogemi landslide (1924), Quebec, Canada, the clay slope was being eroded at an alarming rate due to the high amount of wastewater disposal into a natural clay gully. Noticeable effects of these erosions were observed three months before the catastrophic landslide through smaller slides in the valley. In addition, significantly high rainfall intensity was recorded two days before the landslide, and just the day before the event, a magnitude VII-VIII (modified Mercalli scale) earthquake having an epicenter very close to the landslide location was recorded. After the disaster took place, as mitigation measures, immediate backfilling was done, drainage valves were opened to reduce the pore water pressure on the slope, and other measures of waste disposal were introduced. As a result of such actions, erosion was prevented in the new backfill. Interestingly, another earthquake took place with greater intensity (magnitude IX) with the same epicenter four months later no damaging effect was observed on the slope.

Odenstad (1951) discussed the Skottorp landslide (1946) near the Lidan River in the Norweigian quick clays (highly sensitive clays) and illustrated that the pre-failure slope stability was found to be 0.77-1.34 by the slip circle method. He conferred that the frequent erosion of the river bed and strength reduction due to the leaching out of salt, overall, the process of valley formation could be the reasons for this reduced slope stability and reasoned that such slopes are susceptible to retrogressive failure with a sudden increase of pore water pressure due to rainfall. South Nation River landslide (1971) was believed to be triggered by the increase of the pore water pressure due to snowmelt and spring flood. However, a geotechnical investigation of a county road crossing about 460m south of the landslide location revealed that the slope was marginally stable due to embankment erosion over the years and unfit for a crossing (Eden et al. 1971). The devastating Rissa landslide (1978) initially started from a small excavation activity (Gregersen 1981), but the stability of the slope before failure was found to be marginal due to prolonged erosion. This also highlights that landslides are more likely to occur for a small increase in stresses (heavy rainfall, small excavation, or other reasons) on slopes already at reduced stability due to ongoing erosion over the years.

Crawford and Eden (1964) suggested that sensitive clay slopes become potentially unstable due to the long-term natural process while discussing the causes of the Nicolet landslide (1955). Furre landslide in the quick clays of central Norway (1959) also occurred due to the unloading at the toe of the slope owing to lateral erosion (Hutchinson 1961). Toulnosac (1962), Saint-Jean-Vianney (1971), Basstaad (1974), La Grande River landslide (1987), Lameux Landslide (1993), Sainte-Monique landslide (1994), Saint-Jude landslide (2010), and Saint-Luc landslide (2016) are some other landslides where active stream erosion gradually increased the shear stress at the slope leading to an eventual failure in highly sensitive clays (Colon 1966, Tavenas et al. 1971, Gregersen and Loken 1978, Lefebvre et al. 1990, Evans and Brooks 1994, Locat et al. 2015, 2017, Tremblay- Auger et al. 2021).

Therefore, it can be concluded that the process of valley formation and active erosion of the highly sensitive embankment clays play the primary role in the initiation of large retrogressive failure. Another important aspect to be noted from the above discussion for stability analysis is that these landslides are occurring in the zones of active erosions, that is, landslides keep occurring in the vicinity of the location where previous landslides have been recorded. Therefore, if these zones with active erosion and slopes with marginal stabilities are identified and measures are taken for slope stability improvement, the risk for large retrogressive landslides can be significantly reduced.

3 CASE STUDY OF STABILITY ANALYSIS ON MARGINALLY STABLE SLOPE

From the previous section, it is clear that to assess the risk of retrogressive failure, the slope has to be marginally stable against long-term stability (drained condition). With reduced stability, a small increase in stresses can induce failure of the slope. To further analyze the phenomenon of reduced stability due to erosion in pre-failure conditions and initiation of failure with further small erosion, the Saint-Jude landslide (2010) is selected because a detailed geotechnical investigation of this landslide is available in the literature (Locat et al. 2011, 2017, 2019). The Saint-Jude landslide occurred in the municipality of Saint-Jude, Quebec, about 50 km northeast of Montréal, in a sensitive Champlain Sea clay deposit along the Salvail River (Figure 2). Sixteen similar landslide scars were found on the same location of the landslide from aerial light detection and ranging (LIDAR) surveys (Locat et al. 2017).

The stability of the slope in a drained condition has been studied with the limit equilibrium and finite element methods considering effective strength parameters. The slope geometry and geotechnical properties used in the analysis are presented in Figure 3 and Table 1. This should be noted that triaxial tests for effective strength parameters (i.e., effective cohesion (c’) and friction angle (Φ’)) are only available for the sensitive clay layer (Locat et al. 2019). The drained soil strength parameters for other layers are reasonably assumed as per Locat et al. (2017). The sensitive clay layer was normally to slightly overconsolidated and showed no strain-softening in drained condition.

Table 1: Soil properties used in modeling

Layers	Unit weight γ (kN/m^3)	Strength Parameters c'	Φ'
Sandy crust	18.6	0.0	35.0
Sensitive clay	16.0	6.0	31.0
Silty clay	16.8	7.7	40.0
Clayey silt	19.3	0.0	35.0
Sandy silt	20.7	0.0	40.0

3.1 Limit equilibrium methods

The slope pre-failure state has been modeled using SLIDE/W software in a drained condition to assess whether the slope was marginally stable before failure. In general, the long-term erosion that leads to marginal stability should always be an instability against soil parameters in effective stress conditions. Therefore, stability analysis has been done in drained condition. Safety factor has been obtained with three different methods, Bishop Simplified, Spencer, and Morgenstern-Price, and found to be 1.00, 1.015, and 1.01, respectively. It is observed that in the pre-failure condition, the factor of safety of the slope against long-term stability was very marginal (Figure 4).

After that, a small excavation (about $2m^2$) was carried out to replicate further erosion. The safety factor was significantly reduced below 1 (FS= 0.85, Figure 5) indicating failure. This initial sliding may trigger retrogressive failure with subsequent sliding.

3.2 Numerical modeling

It is well known that limit equilibrium analysis has a number of assumptions that may oversimplify the problem and provide inaccurate results (e.g., limitations regarding the interslice forces, deformation compatibility, convergence, accurate estimation of ground stresses, soil-structure interaction, etc.) (Krahn 2003). A similar analysis has been carried out with the Finite Element Method (FEM), which provides a more robust and accurate framework to evaluate boundary value problems. For this study, Slope stability software RS2 from the Rocscience software suite (https://www.rocscience.com/software) has been used. The Stress Reduction Factor method (SRF method) has been used to assess the stability of the Saint-Jude sensitive clay slope. The 2D plane-strain geometry was modeled with 3000 three noded triangular elements. Bottom and Lateral boundaries were fixed in both directions. The soil was defined as an elastoplastic material with the Mohr-Coulomb failure criterion. The porosity value was set to 0.5. The drained Poisson's ratio is considered to be 0.3, and Young's modulus is taken to be 10,000kPa for sensitive clay layer and 50,000kPa for other layers.

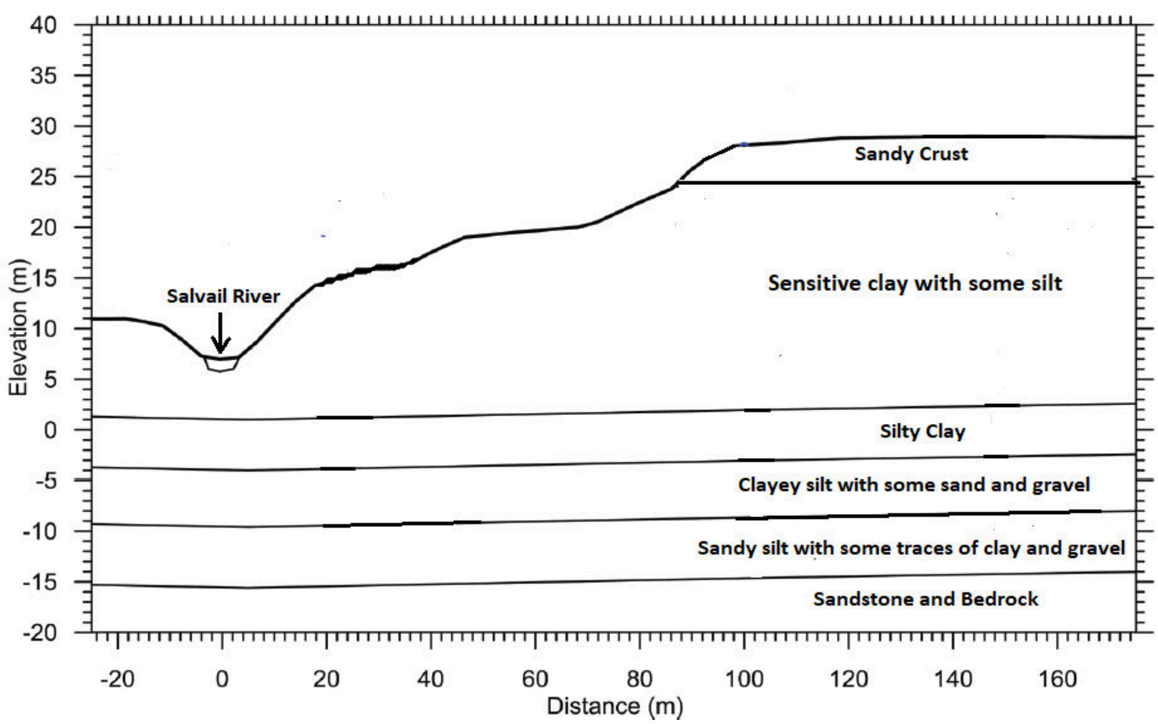

Figure 3. Slope Geometry (Locat et al. 2017).

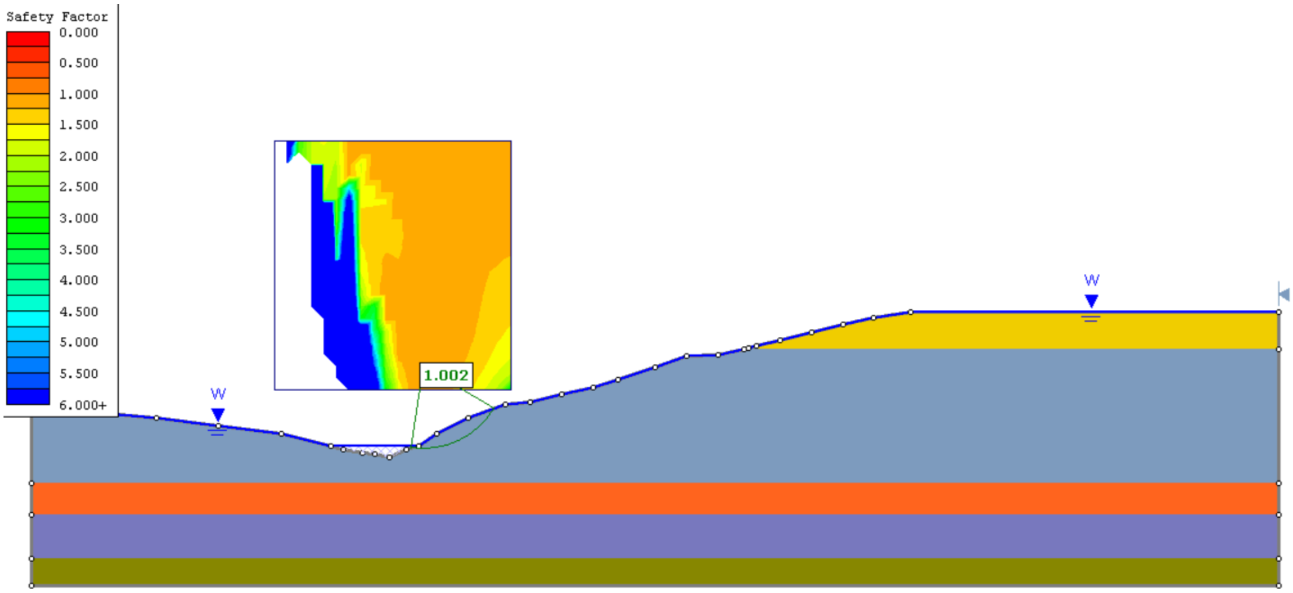

Figure 4. Slope stability for drained condition before failure (Using Bishop Simplified method)

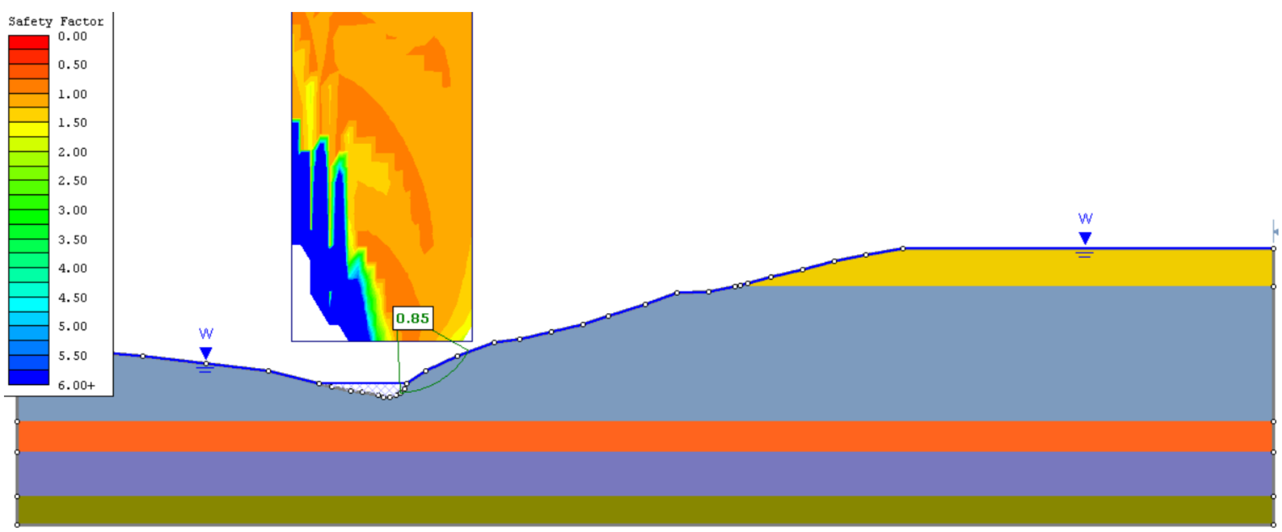

Figure 5. Further reduction of stability with a small excavation (Using Bishop Simplified method)

The FEM safety factors using the SRF method were found to be consistent with the results from the limit equilibrium analysis before excavation (FS=1.01) and slightly higher after excavation (FS= 0.94) as shown in Figure 6 and Figure 7. Unlike LEM, FEM results provide the stress-strain distribution throughout the slope. Moreover, FEM analysis considers important factors like boundary conditions, stiffness parameters, the porosity of the soil, constitutive soil models to capture real soil behavior, etc., which makes the stability analysis more realistic. Nevertheless, for preliminary stability analysis where the main goal is to determine the factor of safety as in this study, LEM is the easiest and most convenient method to execute to obtain satisfactory preliminary results that are comparable to FEM.

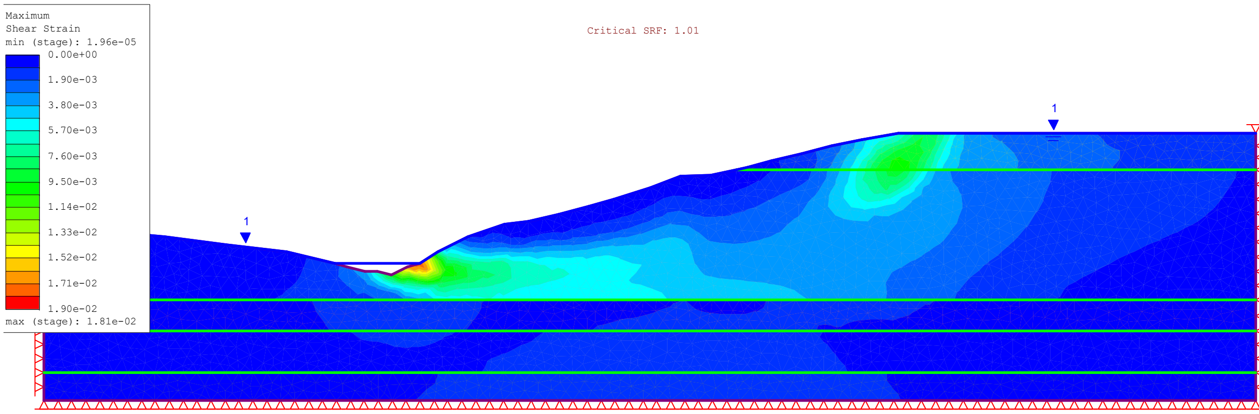

Figure 6. Slope stability for drained condition before failure using FEM (SRF method).

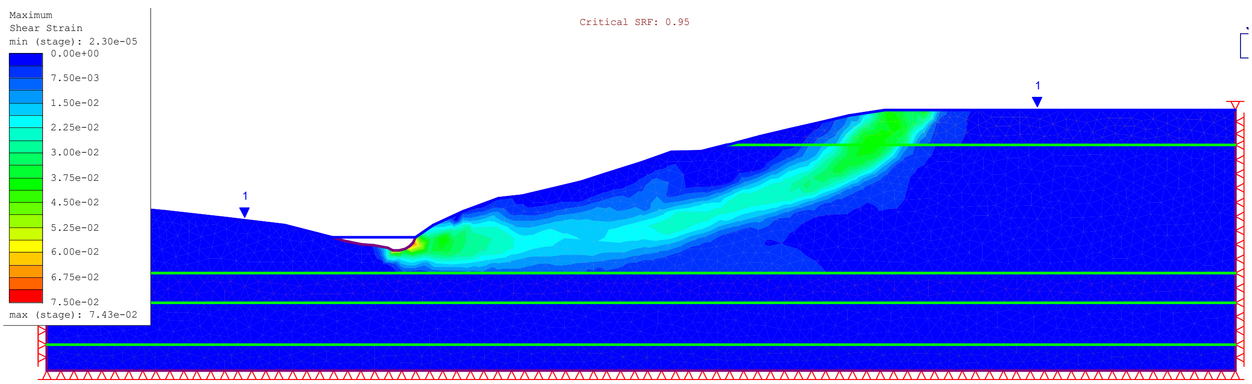

Figure 7. Initiation of failure with a small excavation using FEM (SRF method).

4 CONCLUSION

The stability of the slopes in sensitive clays before retrogressive failure has been investigated. It is concluded that the factor of safety of such slopes just before the final trigger is extremely marginal due to ongoing embankment erosion. Having marginally stable slopes on sensitive clays is a major warning sign for future landslide occurrences because a minor stress increase can trigger a massive catastrophic event. LEM methods are comparable to FEM results in normally to slightly overconsolidated sensitive clays for assessing the pre-failure slope stability. Large landslides can be prevented by regularly monitoring the erosion activities at the locations of previous large landslides and taking adequate measures for slope stability improvement.

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