

# UNDERSTANDING SPREADS IN CANADIAN SENSITIVE CLAYS

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## ABSTRACT

Spreads result from the extension and dislocation of the soil mass above a shear zone, forming horsts and grabens moving and subsiding in the underlying remoulded soil forming the shear zone. They may cover large area (> 1 ha), occurred rapidly with no warning signs, and regular stability analysis do not apply, as they give too large factor of safety when back calculating actual spreads. In addition, they constitute 37% of the 108 large landslides inventoried by the Ministère des Transports, de la Mobilité durable et de l'électrification des transports du Québec (MTMDET) in Quebec (Demers et al. 2014). Spreads are therefore a major threat to population living in areas prone to sensitive clays. This work presents the advancement in our understanding of spreads in Canadian sensitive clays, focusing on research performed on two aspects: (i) synthesis of spreads in Eastern Canada, and (ii) application of progressive failure to spreads.

A total of 14 historical cases were used to depict spreads in Canadian sensitive clays, combining detailed cases of spread from MTMDET database with additional information from literature. Information gathered on these landslides is as follows: topographic data from conditions before and after each landslide from aerial photographs or lidar data in order to interpret the morphology of the slope before the event and the debris; field investigation including boreholes, CPTU, vane shear tests, piezometers, detailed cross-sections and trenches; and laboratory testing including usual geotechnical tests, triaxial tests, direct simple shear (DSS) tests and direct shear (DS). Constant volume ring shear tests (RS) have also being done on a few samples.

Compilation of information from the study of these landslides shows that spreads may concern areas larger than 1 ha. Their retrogression distance varies from 75 to 675 m and their width varies from 145 to 955 m. Their width is generally larger than their retrogression distance. Their shape is typically rectangular or half-circular, but can somewhat vary if they are constrained by topographic barriers (ex: deep gullies or older landslide scar). Craters of spreads are filled with several ridges created by horsts separated by grabens. Horsts are blocks of more or less intact clay having sharp tips pointing upward. Their sides are generally inclined to about 60° with the horizontal. Grabens are blocks of more or less intact soil having flat horizontal tops with trees that can still stand straight after the movement. The failure surface for the spreads studied was found to be almost horizontal and, except for a few cases, located at the elevation of the toe of the slope, or 1 to 2.5 m above or below it. No weak zone seems to be controlling the failure surface location. These observations enabled to conclude that horsts and grabens are the results of dislocation, translation and subsidence of the soil mass above the failure surface with no or very little rotation. It is also believed that these blocks are formed in one large continuous movement and not by the movement of individual horsts and grabens that would slide and translate on after the other. Recent investigations indicate that the failure surface can develop on more than one level, as is seen in the 1971 Casselman case (Durand et al 2016) and the 2010 Saint-Jude spread (Locat et al. 2011b), and reveal that spreads can be complex and need detailed investigations in order to understand the kinematic involved during failure.

When studying the geotechnical properties of the soil involved in the various spreads studied, it can be seen that most spreads occurred in silty clays (< 2 µm between 26 to 85%) having plasticity index varying from 4 to 38% and liquidity index ( $I_L$ ) varying from 0.9 to 3.1. Remoulded shear strength ( $S_{ur}$ ) is consistent with  $I_L$  values and can be lower than 0.07 kPa. Most of the spreads studied occurred in nearly normally consolidated soft to stiff clays (average of 10 kPa <  $S_u$  < 150 kPa and average overconsolidation ratio  $\approx$  1.1). Sensitive clay flowslides tend to occur in clays having  $S_{ur}$  lower than 0.8 kPa and  $I_L$  larger than 1.5 (Demers et al. 2014). Contrarily to flowslides, spreads can occur in clays having lower  $I_L$  and larger remoulded shear strength than what is generally observed for flowslides. As an example, the spread that occurred at Saint-Barnabé involved soil with average  $I_L$  around 1.1 (A. Locat et al. 2017). During undrained shear, strain-softening behaviour has been observed through triaxial tests, DSS tests, DS tests and RS tests.

The implication of the strain-softening behaviour of sensitive clays on the failure mechanism of spreads, suggests that progressive failure is involved in these landslides. Skempton (1964) described the failure mode occurring during progressive failure with the following statement: "[...] if for any reason a clay is forced to pass the peak at some particular point within its mass, the strength at that point will decrease. This action will throw additional stress on the clay at some other point, causing the peak to be passed at that point also. In this way a progressive failure can be initiated and, in the

limit, the strength along the entire length of a critical slip surface will fall to the residual value.” Bjerrum (1967) also presented the idea that progressive failure could explain how failures propagating upslope can be initiated in intact slopes consisting of overconsolidated plastic clays and clay shales. He applied this idea to large retrogressive landslides as a drained or effective stress phenomenon. A. Locat et al. (2011, 2013 and 2015) suggested that spreads may be explained by upward progressive failure. This mechanism could physically explain how a failure can be triggered at the toe of a slope, how it can propagate in a homogeneous deposit, and finally why the soil mass above this failure surface dislocates in active failure, forming horsts and grabens typical of spreads.

A numerical method was developed at Université Laval with the collaboration of the Norwegian Geotechnical Institute (NGI) in order to apply the progressive failure concept to spreads in Canadian sensitive clays (A. Locat et al. 2013). The method uses the finite elements software Plaxis 2D to define the initial stress conditions in a natural slope and Bifurc, a finite element model developed at NGI, to model the progressive failure along a potential failure surface. This method allows for the determination of the susceptibility of a slope to progressive failure by estimation of the magnitude of the disturbance needed to initiate failure and the estimation of the final extent of the failure surface, once the failure is initiated. For now, this method has been applied to 4 different spreads: the 1994 Sainte-Monique spread (A. Locat et al. 2015), the 2005 Saint-Barnabé spread (A. Locat et al. 2017), the 1971 Casselman spread and the 1986 Saint-Luc-de-Vincennes spread (Durand 2016).

What was learned from these first applications of progressive failure to these case studies is that before failure, the initial shear stress along a potential horizontal failure surface was unevenly distributed with, in certain cases, a maximum close to the intact shear strength of the soil. All other parameters considered the same, larger sensitivity (lower large deformation shear strength) leads to larger retrogression distance of the failure surface. When thin shear zones are formed, soils exhibit more brittle shear behaviour, defined here as a rapid decrease of strength beyond the peak shear strength, and the susceptibility to progressive failure is increased, as less unloading of the toe of the slope is needed to initiate the landslide. Also, the stress-strain behaviour of the soil needed to back-calculate the failure is generally much more brittle than the one measured in triaxial compression or DSS tests, with lower large deformation shear strength. RS tests enabling larger shear strain are therefore being used to measure the actual large-deformation shear strength of the soil. In addition, the reduction of the horizontal stress during failure propagation seems large enough to explain the formation of horsts and grabens by active failure of the soil mass.

The next step is now to model in two dimensions, in a similar way as Dey et al. (2015), additional cases of detailed spreads in sensitive clays. Additional testing is also needed with the RS tests in order to see if the measured undrained soil behaviour in the laboratory may give appropriate results for the modeled spreads. Additional back calculated cases of spreads will confidently lead to the determination of appropriate parameters to determine conditions in which spreads occurred and how to prevent them.

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