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Effect of slope runout angle on runout distance of sensitive clay flowslides using the Energy Reduction Factor (F_{ER})

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Abstract

Flowslides in sensitive clays are frequent in Canada as well as in Scandinavia. The retrogression distance of these landslides may be hundreds of meters or more, where the runout distance of the debris can achieve a distance of the same order of magnitude, even over nearly flat terrains. In a context of hazard mapping, both the retrogression distance and runout distance must be considered. A parametric analysis using the energy reduction factor concept is done here to study the effect of the slope angle in the runout area on the runout distance, using a case study where both the rheological and the geotechnical properties of a landslide are known. It is demonstrated that the effect of the runout angle on runout distance is important, with an increase of nearly 60% of the runout distance with an increase of only 1° of the runout slope angle. However, the debris width is not too much affected by this increase.

1 INTRODUCTION

Landslides in sensitive clays are common in Eastern Canada, in Scandinavian countries such as Norway or Finland, and in some raised fjords in Western Canada. When most of these landslides will exhibit retrogression distance less than twice the slope height, some may retrogress hundreds of meters and more. This is the case of spread failures or flowslides (Locat et al. 2011, Demers et al., 2017). Runout distance of the debris for spread is somewhat limited but may reach hundreds of meters for flowslides.

In this paper, we will concentrate on flowslides, which are caused by a succession of rotational landslides. This runout of the debris may affect infrastructures in the runout area, and this needs to be taken into account in hazard assessment. The runout zone is defined as the portion of the terrain extending from the toe of the initial escarpment (before the slide) and the maximum distance reached by the debris. The runout slope angle is than average angle of the terrain underlying the landslide debris in the run out zone prior to the initial failure. Hazard assessment for flowslides in sensitive clays is mostly done using empirical relationships (Strand et al., 2017, Turmel et al. 2018), that considers the retrogression distance or the landslide area in order to evaluate the propagation distance and shape of the debris. The aim of this paper is to evaluate, using one case study, the effect of the runout area angle on the shape of the debris. This will be done using the Alfred landslide (Fig. 1), Ontario, Canada, where geometrical, geotechnical as well as rheological data are available for the back-analysis of the landslide. The energy reduction factor approach (Turmel et al. in press) will be used for the back-analysis of the landslide. Using the back-analyzed simulation results, a prospective analysis will be done to illustrate the effect of the runout slope angle on the debris spreading.

After a short review of flowslides in sensitive clays as well as the energy reduction factor and the numerical modeling approach, the Alfred case will be presented. Results from the back-analysis and the prospective analysis will then be presented, followed by some discussion and concluding remarks.

2 FLOWSLIDES IN SENSITIVE CLAYS

Flowslides in sensitive clays are caused by a succession of rotational failures. This succession of rotational failures is possible when three conditions are met. The first condition is that the height of the backscarp must be high enough that the potential energy (E_p) is higher than the energy required to remold the debris (E_r). The second condition is that the debris consistency when remolded must be liquid enough that they will flow out of the crater. A liquidity index larger than 1.2 or a remolded shear strength of less than 1 kPa was proposed by Lebuis et al. 1983 as a threshold. The third condition is that the newly formed slope is unstable. The succession of rotational failures will stop when there is a change in the geotechnical properties of the material or when there is a change in the stratigraphy.

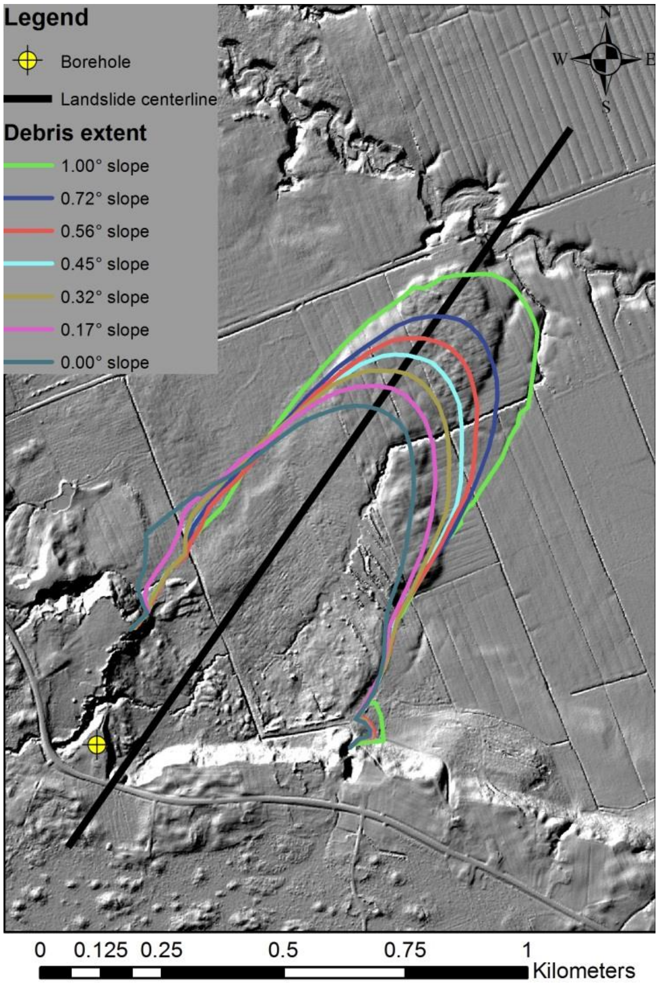

Figure 1. Hillshade of the Alfred landslide, showing the location of the borehole selected for this study, the debris extent for the parametric simulations and the centerline of the landslide.

2.1 Energy reduction factor

The first condition enumerated in section 2 is that the potential energy is higher than the energy required to remold the debris. This condition is necessary because of the properties of sensitive clays, which have high shear strength when in their intact state, but much less resistance in their remolded state. The sensitivity of clays is defined as the ratio between the intact shear strength and the remolded shear strength. It is this low resistance in the remolded state that allows the clay, yet at a constant water content, to flow. In sensitive clay flowslides, most of the transformation of the clay from an intact to a remolded state happens in the first moments after the failure of each slice. This allows the debris to flow out of the crater.

This transition from an intact state to a remolded state, on the other hand, requires a large amount of energy. This energy, hereinafter called remolding energy, is taken from the potential energy of the landslide, and will therefore not be available to be transferred into kinetic energy.

Few studies have focused on the energy needed to bring clay from an intact to a remolded state. This includes studies by Flon (1982), Tavenas et al. (1983) and Yong and Tang (1983). Tavenas et al. (1983) defined the remolding index by:

$$I_r = 100\frac{s_u - s_{ux}}{s_u - s_{ur}} \qquad (1)$$

where s_u is the intact undrained shear strength, s_{ur} is the remolded undrained shear strength and s_{ux} is the shear strength after a certain amount of remolding. Flon (1982) demonstrated that the remolding energy (Er) required to remold a sample is a function of the plasticity index (Ip). Later, Leroueil et al. (1996) showed that for a remolding index of 75 %, the remolding energy per unit of volume is defined as:

$$E_{r75} = 12.5\ s_u I_p \qquad (2)$$

Using the same dataset as Leroueil et al. (1996), Locat et al. (2008) showed that, considering only a remolding index between 10% and 75%, the remolding energy of 16 $s_u I_p$ can be extrapolated for a remolding index of 100%.

From these relationships, it is possible to estimate, knowing the geometry of a landslide, the amount of energy required to remold the debris and to compare this value to the potential energy. In doing so, Vaunat and Leroueil. (2002) defined the destructuration index :

$$I_D = \frac{E_p}{E_r} \qquad (3)$$

For a 100% remolding, the destructuration index would be :

$$I_D = \frac{\rho g H}{16 s_u I_p} \qquad (4)$$

Where ρ is the volumetric mass density of the clay, g the gravitational acceleration and H the height of the center of mass of the landslide relative to the landslide toe. For a numerical modeling perspective, it is also possible to estimate the remaining energy available to be transferred to kinetic energy after remolding. For doing so, the energy reduction factor can be described as:

$$F_{ER} = \frac{\mathrm{E_p} - E_{r100}}{E_p} = \frac{\rho g H\ \ - E_{r100}}{\rho g H} \qquad (5)$$

The energy available for mobility will then be the total potential energy multiplied by the F_{ER}.

2.2 Numerical modeling

For the runout modeling of the landslide, the *r.massmov* numerical model was used (Molinari et al., 2014), in a customized version that was modified in order to be able to use the F_{ER} function as an input (Turmel et al. 2019). This model is an implantation of the MassMov2D model (Begueria et al., 2009) in the Grass GIS, which is freely available with open access to the source code. It is possible using *r.massmov* to model the landslide debris runout over complex topography. Using an Eulerian approach, *r.massmov* solves Navier-Stokes equations using the shallow water assumption. The rheology of the sensitive clay is defined here as a Bingham fluid, because, this rheology describes quite well the rheology of sensitive clays, more specifically of the clay found in the Alfred landslide. In these simulations, the rheological parameters of the sensitive clay are constant throughout the simulation, in the sense that the landslide mass is considered as completely remolded right from the beginning of the landslide. This means that the rupture is not modeled and that the landslide is not in a state of static equilibrium at the beginning of the movement. However, as previously described, the energy used to remold the material between the intact and remolded state is taken into account by the use of the F_{ER}. The boundary condition at the interface between the moving fluid and the terrain is a no-slip boundary condition. No entrainment of material is considered. Finally, the *r.massmov* model allows taking into account that not the whole mass fails at the same time so that a retrogression velocity has to be entered as an input parameter.

In the following simulations, a retrogression velocity of 5 m/s was chosen, as this is approximately the value reported by Tavenas et al. (1971) for the Saint-Jean Vianney flowslide retrogression velocity (he reported a velocity equivalent to a person running at the same speed as the landslide). This is done in the model by using a distance map from the toe of the surface of rupture, and the model calculates at each time step the available material, according to the retrogression velocity.

3 ALFRED LANDSLIDE

The Alfred landslide is located in the Alfred and Plantagenet municipality in Ontario province, Canada, about 65 km East of Ottawa, near the border of the Quebec province. This flowslide has a maximum width of 490 m and a maximum retrogression distance, measured between the toe of the slide and the backscarp, of 280 m. As shown in Fig. 1, the runout distance of the debris is 1000 m, a distance taken from the toe of the landslide. The shape of the debris is elongated with a width that decreases in a regular way, from about 420 m near the landslide toe to 225 m at the maximum extent. The topography before failure was reconstructed using the topography of the adjacent area. Furthermore, the topography of the failure surface was estimated considering that about 20% of the debris remains in the crater after failure (Demers et al. 2014), A total volume of 949 000 m^3 was found for the landslide. A topographic profile showing the extrapolated failure surface along the central line of the landslide (Fig. 1) as well as the pre-failure topography is shown in Fig. 2.

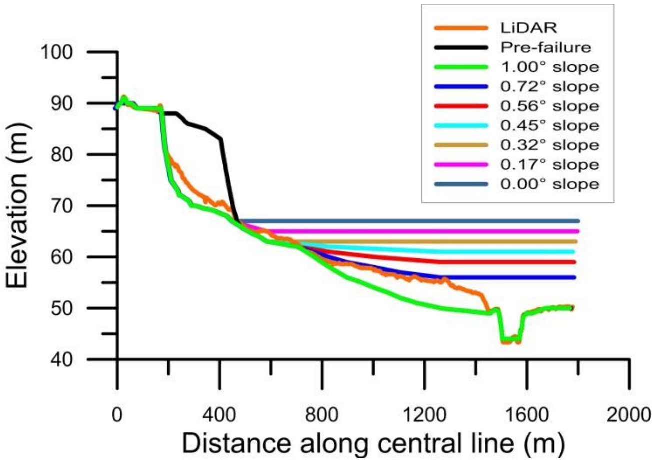

Figure 2. Topographical profile along the center line for the different scenarios modeled in the analysis. Vertical exaggeration: 20X

The geotechnical profile from the borehole located in Fig. 1 is presented in Fig. 3, adjacent to a CPT profile done at the sample location. At Alfred, there is a ~5 m layer of sand overlying a 17 m thick clay deposit. The liquidity index for the whole profile is over 1.2, except for the deeper sample with a liquidity index of 1.1. The plasticity index varies between 21 and 43, the higher values being for the shallower samples. The mean plasticity index for this deposit is of 29.9%. Between a depth of 5 to 10 meters, the remolded shear strength is slightly over 1 kPa. Between 10 and 21 m, the remolded shear strength is lower than 1 kPa. The mean remolded undrained shear strength is 0.66 kPa. The intact undrained shear strength varies mostly between 30 and 46 kPa, with a mean value of 37 kPa. The scatter in the undrained shear strength may be explained by the stratified nature of the material, that can also be seen on the CPT profile. Grain size analysis for the different samples shows that except for the three shallower samples and the deeper sample which shows a fair amount of sand, the whole deposit consists of silty clay. Salinity profile shows that the salt was completely leached from all the samples, with salinities lower than 0.5 g/l. A unit weight of 17.5 kN/m^3 was considered in the analysis.

Rheological tests were conducted for samples PS04 to PS17. These tests were conducted either using a cone and plate geometry or coaxial cylinder geometry and in some cases, both geometries were used on the same sample and showed the same rheology. The results are shown in Fig. 4. As can be expected from the geotechnical properties, the samples PS04 to PS07 shows different rheology as the deeper samples, with a yield strength of approximately 300 Pa, and very high viscosity (> 50 Pa.s). A plateau that can be described as Bingham's behavior was not attained for samples PS05 and PS06. For all the samples below PS07, a clear Bingham behavior can be described when the shear rate is over 1 s^{-1}, with yield strength between 75 and 300 Pa, and quite low viscosities. When the shear rate is lower than 1 s^{-1}, the yield strength is lower than 100 Pa, but with very high viscosities. Up to now, no rheological model allows taking into account the very low shear strength but very high viscosity at a very low shear rate, Bingham parameters using rheological parameters over $1s^{-1}$ will be used in the analysis. Since a plateau was not reached for some of the samples, it is difficult to assess mean rheological properties for the material involved in the flowslide. However, it can be hypothesized that a mean value around 200-250 Pa can be considered for the yield strength. The effect of the mean value of the yield strength value will be demonstrated in the results section.

4 SIMULATIONS

The results will be presented in two steps. First, a back-analysis of the landslide mobility will be conducted, considering 1) geotechnical parameters to derive the F_{ER} value and then calculate the yield strength necessary to obtain the proper landslide runout, or 2) using mean yield strength to determine a F_{ER} value. The second portion of the results will use back-analyzed parameters to do a prospective analysis of the effect of the runout zone slope angle on the shape of the debris.

Considering the geometrical constraints of the slide (a mean height of the slide at 22 m was considered) as well as mean geotechnical properties of the material, as reported in the preceding section, an F_{ER} value of 0.074 can be found using eq. 5. Using this value as an input in the numerical modeling, a parametric analysis of the influence of the yield strength on the runout distance (Fig. 5b) shows that a yield strength of 113 Pa is necessary in order to obtain the observed runout distance of 1000 m. The runout extent for this simulation is shown in Fig. 1 (1.00° slope), with, as background, the hillshade derived from the actual topography.

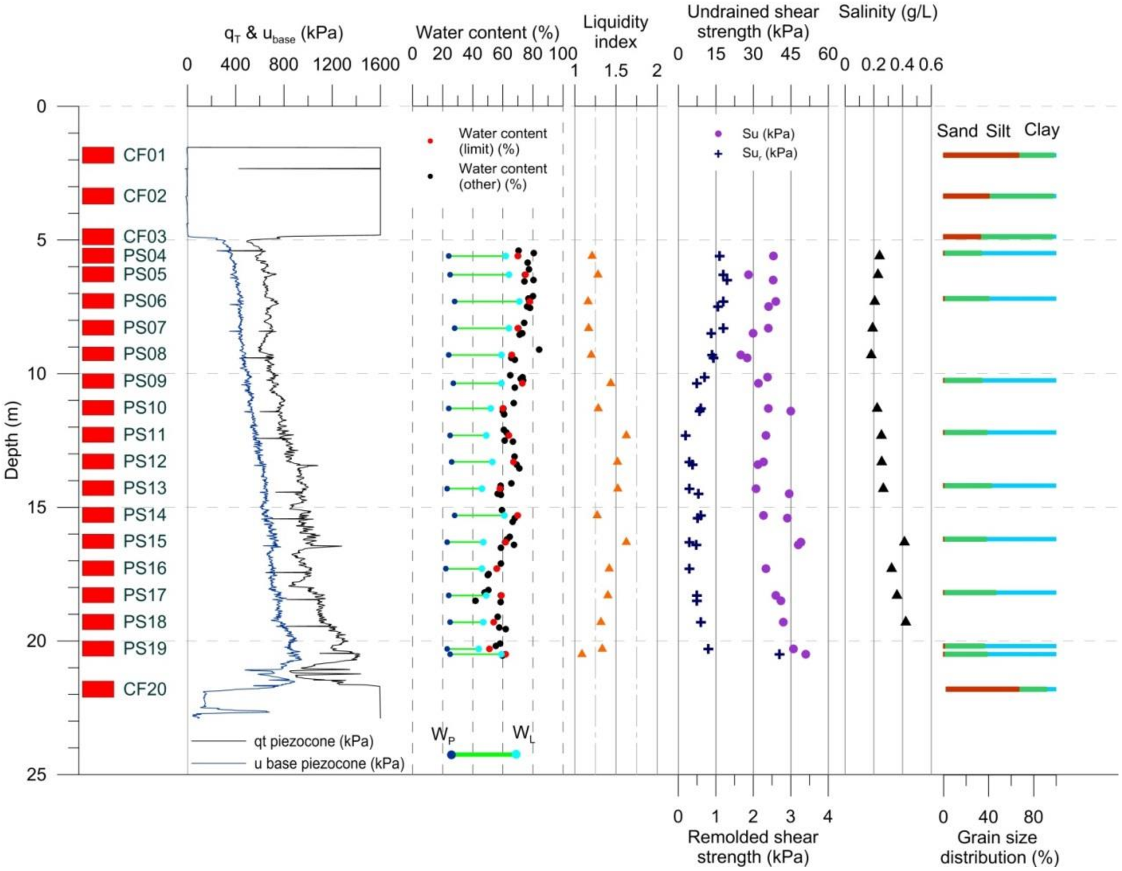

Figure 3. Geotechnical and CPTU profile at the location of the borehole identified in Figure 1.

Considering mean rheological values, i.e. a mean yield strength between 200 and 250 Pa, F_{ER} values between 0.13 and 0.16 are necessary to obtain the proper runout distance (Fig. 5b), higher F_{ER} values than what were found using the geotechnical properties of the material.

For the purpose of the prospective analysis on the effect of the runout slope angle on the runout behavior, results will be presented using a yield strength of 200 Pa with a F_{ER} of 0.13. Results obtained using 115 Pa and a F_{ER} of 0.074 are similar. For the purpose of this prospective analysis, the topography of the area was modified in order to change the runout zone angle. The different profiles used for the parametric analysis are shown in Fig. 2. As shown, 6 different configurations were used, with mean slope angles varying between 0 and 1 degree.

Results from the simulations are shown in Fig. 1 and 6, where Fig. 6 illustrates the effect of the slope angle on the runout distance and Fig. 1 shows in plan the runout extent for the different simulations. Results from this prospective simulation show that there is an almost linear relationship between the mean runout angle and the slope angle. Between a slope angle of 0° and a slope angle of 1°, there is a difference of almost 450 meters of runout distance, considering everything else being equal.

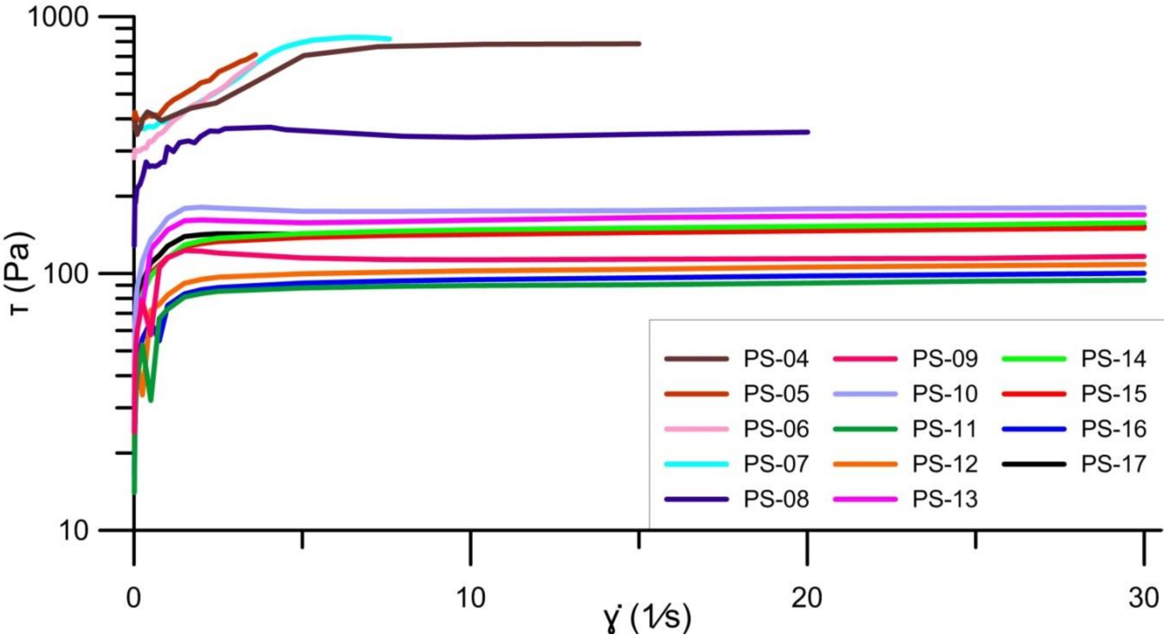

Figure 4. Results from rheological tests done on samples taken at the location of the borehole. The samples depth are referenced in Figure 3. Note that the Y-axis is on a logarithmic scale.

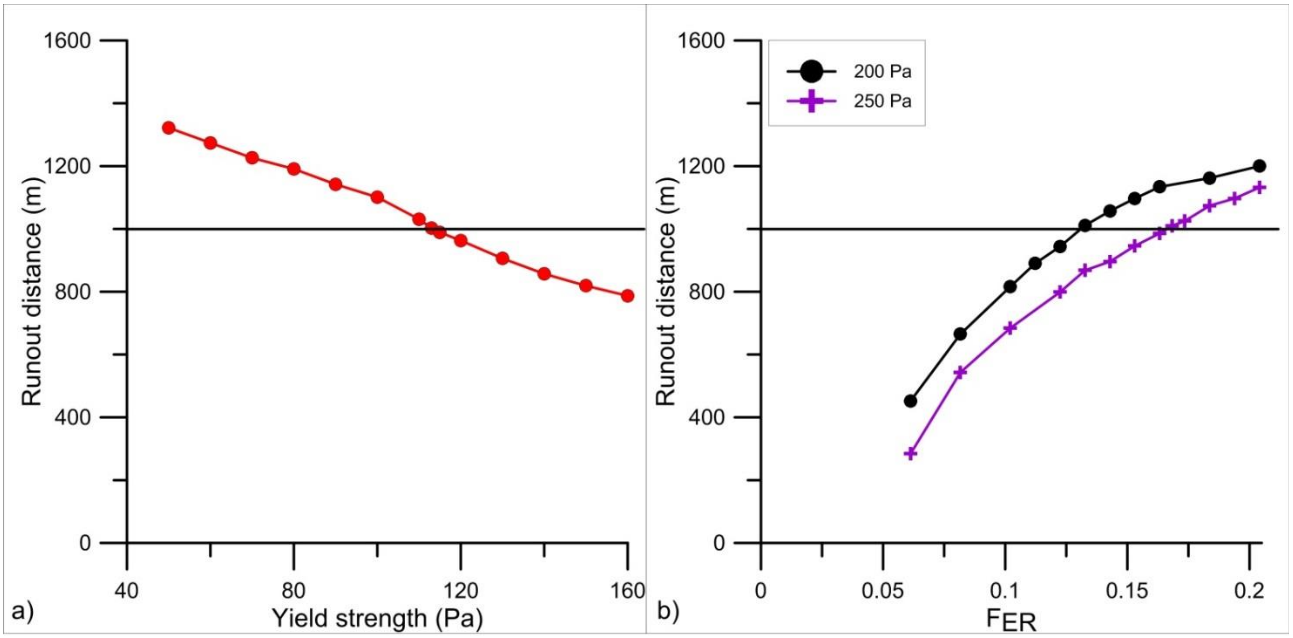

Figure 5. Results from the back-analysis, using a) an Energy reduction factor of 0.074 as determined with geotechnical properties and b) using mean rheological properties.

5 DISCUSSION

In this paper, we used the energy reduction factor concept to back-analyze the Alfred landslide and use the values found in this back-analysis in order to conduct a prospective analysis on the influence of the runout slope angle on the runout distance. These two different analyses will be discussed in the following paragraphs.

5.1 Back-analysis

Back-analysis of the Alfred landslide was made using two different approaches, the first one is to consider the F_{ER} value found using mean geometrical and geotechnical properties of the material, and the second was to consider mean rheological values in the modeling. Results from the simulations show that the shape of the deposit is comparable between the modeling and the reality. The western limit of the deposit is almost exactly the same. However, there is more difference on the eastern side of the deposit, results from the numerical model being about 80 m wider than the reality at the distal end. However, the morphology of the real debris shows on the east side a reentrant, that might have been caused by a morphology in the runout area that was not captured in the back-analysis, or by other factors that were not modeled such as the presence of stiffer material.

Using the F_{ER} of 0.074 found with geotechnical properties, a yield strength of 115 Pa must be used in order to obtain the proper runout distance. Such a low yield strength is approximately the mean yield strength of the samples PS09 to PS17. On the other hand, samples PS04 to PS07 shows higher yield strength, the mean yield strength value considering these 4 samples should be higher, with a value in the range of 200-250 Pa. Using such yield strength, a F_{ER} value between 0.13 and 0.16 is found, which are higher values than what has been estimated using geotechnical properties. As the flow of a yield stress fluid shows plug flow, an hypothesis coulrd be that the value of the lower portion of the sensitive clay will be controlling hr flow , since the upper layers would be transported as a plug flow.

It must also be noted that in the analysis for the F_{ER} using geotechnical parameters, a 16 s_uI_p value was used to determine the energy required to remold entirely the sensitive clay. This value was determined by Locat et al. 2008 using data from Flon (1982), Tavenas et al. (1983) and Yong and Tang (1983). This set of data shows some scatter, as not all the clays that were tested had exactly the same behavior. Using the F_{ER} values determined in the analysis, one can found values for 100% of remolding varying between 14.5 s_uI_p and 15.1 s_uI_p, which are slightly below the value found by Locat et al. 2008.

5.2 Prospective analysis

Prospective analysis results show that a small slope angle in the runout area may have a large influence on the runout distance of the debris, everything else being equal. Between a flat slope and a 1° slope, prospective analysis for the Alfred landslide shows an increase in the runout distance of 57%, which is significant. However, as shown in Fig. 1, the debris width is not too much affected by the increase in slope angle in the runout direction. The effect of the runout area angle should then be considered in the context of hazard mapping. However, it must be noted that this increase in terms of percentage might be a function of the rheological properties of the flowing material, more case studies are then necessary before applying these observations.

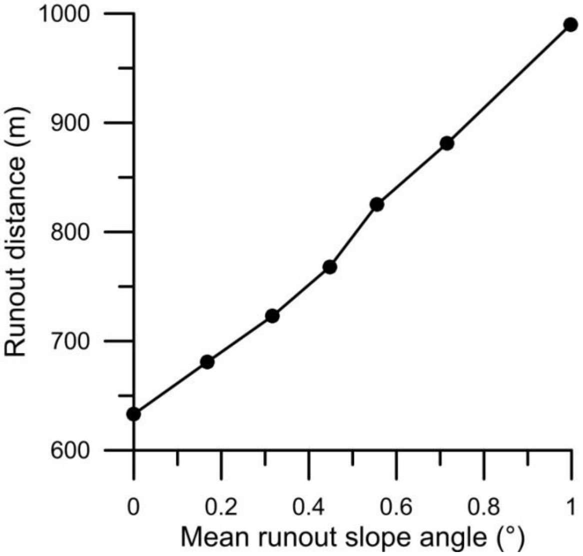

Figure. 6 Effect of the mean runout slope angle on the landslide runout distance

6 CONCLUSION

A back-analysis of the Alfred landslide was done in order to analyze the effect of the slope angle in the runout area on the runout distance. The back-analysis, using the Energy reduction factor, showed a good agreement between the shape of the modeled deposit and reality. Furthermore, the yield strength necessary to reproduce the runout extent is close to the yield mean strength of the most sensitive part of clay that is entrained in the landslide. This might represent the fact that the top layer will be transported in such landslide as a plug flow, and that the most important part of the landslide for this kind of analysis is the most sensitive portion (weakest). However, this might also represent an overestimation of the energy required to remold the debris. The prospective analysis was done with the back-analyzed parameters and shows that the runout angle has a great effect on the runout distance of sensitive clay flowslides. A difference between 0° and 1° of runout angle makes a 57% difference in the runout distance. However, the width of the debris is not so affected by this slope angle.

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