THE ENERGY REDUCTION FACTOR AS A NEW PARAMETER TO INTEGRATE IN SITU RHEOLOGICAL DATA IN THE NUMERICAL MODELING OF SENSITIVE CLAY FLOWSLIDES

GEO OTTAWA 2017

Turmel, D., Locat, J.
Département de géologie et de génie géologique, Université Laval, Québec, Canada
Locat, A., Leroueil, S.
Département de génie civil et de génie des eaux, Université Laval, Québec, Canada
Locat, P., Demers, D.
Ministère des Transports, de la Mobilité durable et de l'Électrification des transports, Québec, Canada

ABSTRACT
Sensitive clays are prone to various types of landslides; among them are flowslides that may affect hectares of land. Debris from those slides has a high mobility, with run out distances that may extent hundreds of meters in relatively flat terrain. Most studies on the mobility use apparent rheological properties in order to back-calculate the behaviour of the landslides. This works well for the back-analyses of landslides, but is of little help in a context of hazard mapping. In this study, real rheological data acquired with a rheometer are used in order to analyse the post-failure behaviour of a flowslide in sensitive clays. A new method, using the destructuration index concept, is used in order to estimate the remaining energy available as kinetic energy for run-out, thus introducing an energy reduction factor. This method is applied on a sensitive clay landslide which took place in Quebec, and where rheological and geotechnical data are available. The numerical modeling of the landslide run-out is done in a full 3D model.

RÉSUMÉ
Plusieurs types de glissements de terrain peuvent survenir dans les argiles sensibles, certains, tel que les coulées argileuses, pouvant affecter de grandes superficies. En effet, la distance de parcours des débris de coulées argileuses peuvent atteindre des centaines de mètres, et ce même sur des terrains ayant une pente très faible. La plupart des études sur la mobilité des coulées argileuses utilisent des paramètres rhéologiques apparents pour pouvoir modéliser à rebours le phénomène, paramètres qui sont très différents des paramètres mesurés en laboratoire. Une nouvelle méthode, basé sur un indice de destructuration et sur un facteur de réduction d'énergie, est introduite dans cet article, permettant d'utiliser les données rhéologiques acquises à l'aide d'un rhéomètre pour pouvoir modéliser la distance de parcours d'une coulée argileuse. Cette méthode est appliquée, à l'aide d'un modèle numérique de terrain tridimensionnel, à un glissement ayant eu lieu au Québec.

1 INTRODUCTION

In order to be able to accurately assess the risk of landslide hazards in sensitive clays, two parameters must be established, the first one being the retrogression distance of the landslide, and the second one the run-out distance of the landslide debris. Most landslides in sensitive clays show relatively low run-out distance, so geometric relationships may be used in risk assessment. However, some landslides, such as multiple retrogressive landslides, or flowslides, have run-out extent that may extent hundreds of meters, and numerical simulation tools need to be developed in order to be able to accurately describe the extent of the landslide debris. Such a model was recently developed, and was able to model some landslides that happened in eastern Canada (Turmel et al. 2017a, Turmel et al. 2017b, Locat et al. 2017). However, this model, like other numerical models used in landslide run-out analyses, is using calibrated (back-calculated) rheological parameters that are not the rheological parameters of the material itself. It is then difficult to apply these numerical models for a prospective analysis.

The difference between the calibrated rheological parameters used obtained in the back-analysis of these landslides and the material rheological parameters is due to some aspects of the landslide that are not taken into account in most numerical models, i.e. the amount of remolding of the material. In order to be able to flow, the sensitive clay has to be remolded, and this remolding requires energy.

When remolded, sensitive clays show an important decrease in their shear strength, and will, when the liquidity index is high enough, flow as a fluid. Some studies were made in the past on the energy needed to remold sensitive clays. With clays from Eastern Canada, Flon (1982) defined the remolding index (I_r) as

$$I_r = \frac{c_u - c_{ux}}{c_u - c_{ur}} \quad [1]$$

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

$$E_{r75} = 12.5\, c_u I_p \qquad [2]$$

For a remolding index of 100%, the 12.5 factor in eq. 2 have to be replaced by 16 (Locat et al. 2008).

Locat et al. (2008), using Flon (1982) as well as Yong and Tang (1983) results, integrated this relation with the destructuration index (I_D), defined by Vaunat and Leroueil (2002), to estimate the degree of remolding of clays. This index is the ratio between the potential energy of a landslide and the energy required to remold a sample:

$$I_D = \frac{E_p}{E_r} \qquad [3]$$

For a complete remolding, Locat et al. (2008) showed that the destructuration index is equal to:

$$I_D = \frac{\gamma H_g}{16 c_u I_p} \qquad [4]$$

Where H_g refers to the vertical distance between the center of mass of the landslide before failure and the center of mass of the debris after failure.

When remolded, sensitive clays flows like a fluid. The rheology of eastern Canada clays has been studied since the 1980's, with the work of Locat and Demers (1988). They used rotational rheometer, using concentric cylinder geometry, to investigate the effect of liquidity index of clay samples on the viscosity (μ) and yield strength τ_0 of the fluid. They also showed that the behavior of sensitive clays can be described as Bingham or Herschel-Bulkley fluid. These fluids can be described by the following relationship:

$$\tau = \tau_0 + k\dot{\gamma}^n \qquad [5]$$

In this relation, k is called the consistency index, and is equal to the viscosity when n, the flow index, is equal to one, and $\dot{\gamma}$ is the shear strain rate. For a Bingham fluid, n is equal to one.

In this paper, we will back-analyse the run-out of the the Rivière Saint-Jean (RSJ) landslide (Fig. 1). For this landslide, rheological and geotechnical studies were made, and using these data, we will try to figure out how much energy is left after the remolding of the material, and available as kinetic energy. After a brief methodology section, a presentation of the RSJ landslide will be made. Results of the simulations will then be presented, followed by a discussion about how the remolding energy may be taken into account in the modeling, and if this parameter may be estimated via the geotechnical properties of the material.

2 METHODOLOGY

2.1 Geotechnical and rheological parameters

For the RSJ landslide, samples from one borehole were available, and geotechnical parameters were acquired for some of the samples. Standard procedures were used in order to obtain liquid limit, plastic limit as well as intact undrained shear strength and remolded undrained shear strength. These procedures won't be elaborated here.

These samples were also tested for their rheological parameters at their natural water content and salinity. The viscometer used in this study is the Thermo Scientific HAAKE Viscotester iQ, used in controlled rate measuring mode. Two different geometries were used, depending on the rheological parameters. The first geometry is the concentric coaxial cylinder, using the CC38 cylinder, and the methodology is described in Locat and Demers (1988) and includes dynamic response of the soil as well as hysteresis. The second geometry used is with the FL22 vane. To the author's knowledge, this is the first time a vane mounted on a viscometer is used on sensitive clays to measure rheological parameters such as viscosity and yield strength. This geometry implies that the gap between the vane and the outer cylinder cannot be considered as a small gap, so the relations to obtain the shear rate is dependent on the material, which is not the case when the gap is small such as when the coaxial cylinder geometry is used. Demonstration on how to use the vane geometry for rheological measurements is not relevant for this paper, so the reader is referred to Turmel et al. (2017a) for a complete discussion and demonstration on how to use vane geometry for the characterization of sensitive clay rheology.

2.2 Numerical modeling

The numerical model used for the analysis is the interFoam module of the OpenFOAM software. OpenFOAM is a set of C++ modules used to build solvers to simulate specific problems in engineering mechanics (Weller et al. 1998). InterFoam is a solver, in three dimensions, for two incompressible fluids. It uses the Volume of Fluid method to resolve Navier-Stokes equations over a finite-volume mesh (Deshpande et al. 2012, Turmel et al. 2017b).

For the simulations, the topography before the landslide is imported and the volume occupied by the landslide mass is modeled as completely remolded. The ambient fluid is air. The software allows using, among other rheologies, Bingham or Herschel-Bulkley rheology.

Two kinds of simulations were undertaken. The first one, called classic one, consists of calibrating the rheological properties of the remolded clay in order to obtain the proper run-out distance for the landslide.

The second one is an innovative technique, which consists of using the rheological properties of the material in the simulation. To be able to obtain the proper run-out distance for the landslide, the remolding energy, which is not taken into account in the classic simulation, is taken into account by reducing the potential energy that is available to be transferred to kinetic energy. This is done by introducing an energy reduction factor (E_{RF}), which is multiplied, in the numerical model, to the potential energy.

In all the simulations, the viscosity was chosen as 1:1000 of the yield strength, as it is the ratio generally observed in laboratory for clayey soils (Locat, 1997).

3 RIVIÈRE SAINT-JEAN LANDSLIDE

The Rivière Saint-Jean landslide studied here took place at the end of May 1970. This landslide is located on the north shore of the Saint-Lawrence estuary, approximately 140 km east of Sept-Îles. This multiple retrogressive landslide has a width of about 190 m, with a maximum retrogression distance of about 210 m (Fig. 1). According to Ministère des Transports, de la Mobilité durable et de l'Électrification des transports (MTMDET) archive documents, the debris did spread approximately 245 m (800 feet) on the intertidal zone. These archives are based on witness account, and no photography or other documents attest this runout distance. As shown on Fig. 1, all the debris are now eroded. It is then possible that the runout extent is greater than the one modeled here, as will be discussed.

The post-failure topography shows a step in the south-east portion of the landslide, the lower floor portion being at an elevation of 5 meters, and the higher one at an elevation of 9 m. The exact location of the failure surface is unknown, but it can be considered that 10-15 % of the debris stayed in the scar. The natural elevation of the ground is of 16 in the eastern portion, 26 m behind the back scarp and 25 m in the western portion. The mean elevation of the terrain before failure would be at around 20-21 m of elevation. The total volume of the landslide is approximately between 350 000 and 400 000 m^3, if we take into account that 10-15% of the debris stayed in the scar.

Samples from a boring located 20 m north of the landslide (Fig. 1) were made available for this study by the MTMDET. Five samples were analyzed and the geotechnical profile is shown in Fig. 2. This shows that, for the whole clay deposit over 0 m of elevation, the liquidity index is over unity, with an average value of 2.1. The maximum liquidity index values are for the PS-3 and PS-5 samples, located at elevations of 15.25 m and 11.25

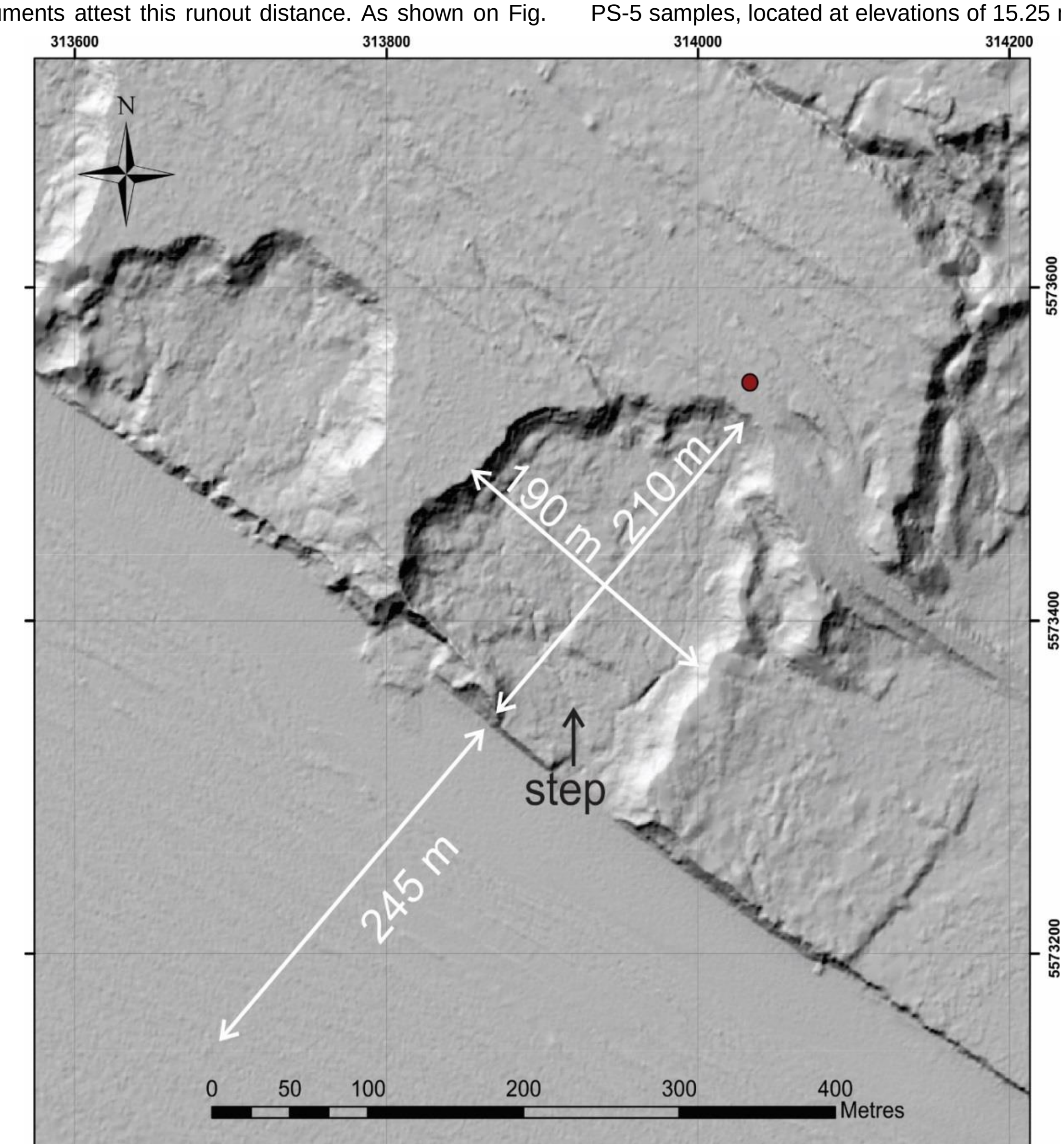

Figure 1. Main geometrical characteristics of the RSJ landslide. The red dot represent the location of the borehole. Coordinates are in NAD83 MTM 5.

m respectively. Plasticity index for all the samples is about 10 %. The intact shear strength, measured in the laboratory using fall cone test, is consistent with field vane measurements, with values around 45-50 kPa. The remolded shear strength for all the samples is low, with values below 1 kPa.

Results for rheological experiments are presented in Fig. 3. As mentioned in the methodology, all samples, except PS-9, were tested with the coaxial cylinder geometry. For the TM-1 and PS-7 samples, the bi-linear behavior can well be recognized. For the other results the Bingham rheology describes well the results obtained. If we consider, for all the samples, that the material obeys the Bingham law, the yield strength for the TM-1, PS-3, PS-5, PS-7 and PS-9 samples are of 475 Pa, 41 Pa, 61 Pa, 204 Pa and 377 Pa respectively. Table 1 reports the yield strength values as well as viscosity and elevation of all the samples.

Figure 2. Geotechnical profile of the borehole located on Fig. 1.

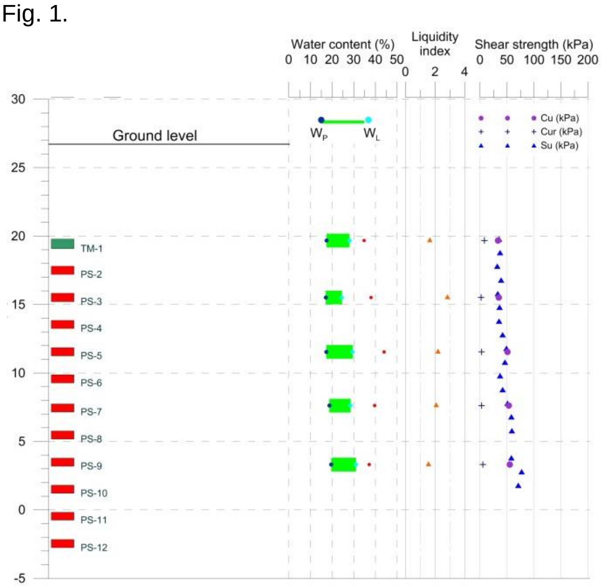

Table 1. Rheological and geotechnical parameters of the tested samples

Sample #	Water content (%)	Liquidity index	Elevation (m)	Yield strength (Pa)	Viscosity (Pa.s)
TM-1	34.7	1.6	19.7	475	14
PS-3	38.0	2.8	15.5	41	0.15
PS-5	44.2	2.2	11.5	61	0.12
PS-7	39.6	2.1	7.6	204	0.18
PS-9	37.2	1.6	3.3	377	0.7

4 SIMULATION RESULTS

Figure 4 shows the influence of the yield strength on the run-out distance of the debris. Three yield strength, between 3500 and 4500 Pa were tested, and the run-out distance varied between 227 and 268 m respectively. In order to obtain a run-out distance of 245 m, a yield strength of 4000 Pa need to be used in the classic simulation (Fig. 4). Figure 5 shows the velocity of the frontal element of the landslide. Two different peaks in the velocity can be seen, one after a few seconds with a velocity of 13 m/s and a second after 20 seconds with a velocity of 11 m/s.

The other simulation was done using a fixed value of yield strength of 270 Pa, which is more representative of the deposit, considering the rheological parameters obtained in the laboratory. This value would correspond to an IL value of 1.7 using Locat (1997) relationships between the liquidity index and the yield stress. Using this value of yield strength, it is found (Fig. 6) that in order to be able to reproduce a run-out of 245 m, an E_{RF} value of 0.066 is needed. The parametric analysis shows that a E_{RF} between 0.061 and 0.077 will lead to a variation between 230 and 275 m of run-out distance. The variation of the frontal velocity vs time is shown on Fig. 5. As with the other simulation, two peaks can be seen, but with lower velocities. The first peak shows velocity of about 3.5 m/s while the second peak shows velocity of 2 m/s.

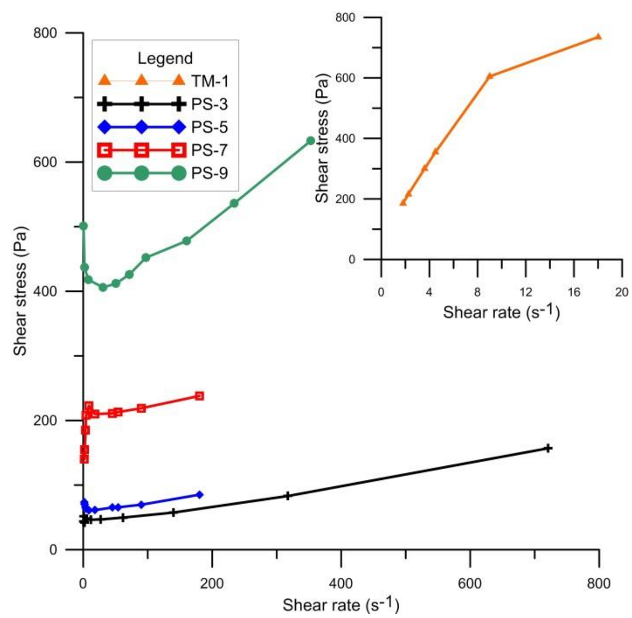

Figure 3. Results of the rheological experiments for the five samples tested.

5 DISCUSSION

Two different kinds of simulations were made for the same landslide, a classic simulation and a simulation where the value of gravitational acceleration was lowered. Both of these simulations have the same problem, in which they consider, from the beginning of the movement, that the material is completely remolded, which is not the case. In the classic simulation, the hypothesis is that there is no energy that is required in order to remold the material, but that the shear strength of the remolded material is much higher than the laboratory value. For the second kind of simulation, the hypothesis is that the value of the yield strength used in the simulation is the same than that obtained in laboratory, and that there is a loss in energy due to the remolding of the material, which will lead to a reduction in the potential energy available to be transferred as kinetic energy. It is possible with the two kinds of simulations to reproduce the run-out extent of the landslide. However, the velocity profiles obtained are really different, in that sense that with high yield strength, the acceleration and deceleration are fast, while with the lower yield strength, the acceleration and are slower. Velocities reached by the material are also very different, with higher velocities in the classic modeling. Velocities reached by the simulations that use the correct rheology may be more realistic than the ones reached with the classic simulation.

In a perfect model, one would need to simulate the propagation of the debris by simulating the remolding of the material, or in other words by starting the simulation with intact material and, by the help of constitutive equation that describes material remolding, simulate the entire process. The new approach presented here is between the classic approach and the perfect model, in the sense that it is using the rheological parameters of the material, but the remolding process is not modeled. However, one parameter still has to be calibrated in order to be able to model the exact run-out, i.e. the amount of energy that is available as kinetic energy.

The destructuration index, as defined in Eq. 4, could be used in order to estimate this parameter. In Eq. 4, the numerator represents the potential energy where the denominator represents the remolding energy. Using these two terms, one may calculate the ratio of energy available as kinetic energy, which should also correspond to the energy reduction factor (E_{RF}):

$$E_{RF} = \frac{\mathrm{E_p} - E_r}{E_p} = \frac{\rho g H - 16 c_u I_p}{\rho g H} \qquad [6]$$

Where H will be considered as half the slope height. The other parameters were previously described. It should be noted that the geotechnical parameters are mean values for the deposits. Therefore, samples should be taken at intervals over the borehole which best describe the characteristic of the deposits.

For the RSJ landslide, considering that the mean elevation of the natural terrain was at an elevation of about 20-22 m, the value H is considered as 10-11 m. It can also be considered that the unit weight of the clay will be around 17 kN/m^3. The mean undrained shear strength is approximately 47 kPa and the mean I_p is 0.1. Considering the above values, an E_{RF} value between 0.55 and 0.57, meaning that about 55% of the potential energy may be transferred into kinetic energy. This also means that, for this landslide, about 45% of the energy is used to remold the clay. The 45% value has to be compared with the 0.066 value found in the numerical simulation.

There is a disagreement between the value found in the numerical model and the value found using the destructuration index. However, this is still a preliminary study and more work need to be done on the different parameters used to estimate the potential energy that can be used as kinetic energy. Furthermore, more effort is needed in order to test if the rheological parameters used in the simulation are really representative of the deposit as well as if the relation [2] is valid. In that sense, it should be noted that for only one experiment achieved a remolding index over 85% (Locat et al. 2008), so there may be some uncertainty in the factor "16" for a 100% remolding. More laboratory work is needed, in order to characterize the rheology of the material as well as the remolding energy of the material.

Another possibility is that the height used in eq. 6 should be half the height of the initial fall of the soil column as compared to half of the height of the total slope. In that sense, since the failure surface is at an elevation of approximately 4 m in the lower portion of the landslide, the height of the fall will be of approximately 10 m. The H value considered will then be of 5 m, which correspond to a E_{RF} value of 0.115. The same value would be obtained on the upper part of the landslide. This value is more consistent with the value found in the numerical modeling.

Another possibility may be that some of the debris did flow in the St. Lawrence estuary and were not visible by the witness that account for the landslide. It will then be needed to use this approach on other landslides where the pre- and post-failure topography are known.

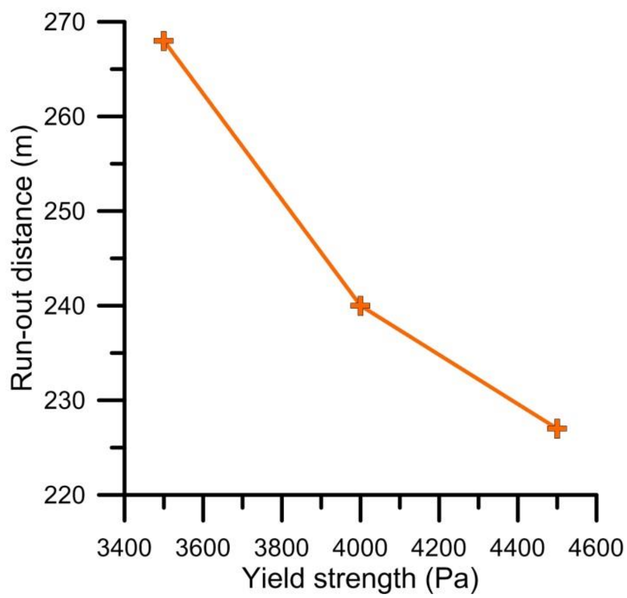

Figure 4. Effect of the yield strength on the run-out distance

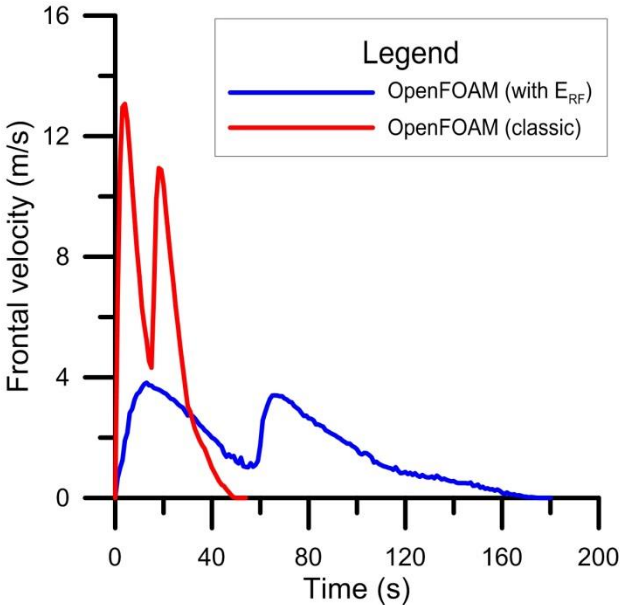

Figure 5. Velocity profiles for the frontal elements of the RSJ landslide.

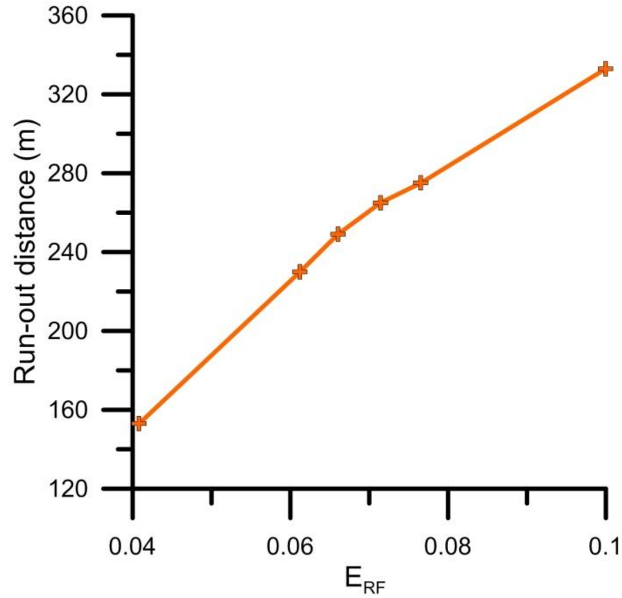

Figure 6. Effect of the E_{RF} used in the simulation on the run-out distance of the RSJ landslide.

6 CONCLUSION

Most back-analyses in run-out modeling are done by modifying the rheological properties of the landslide material, in order to obtain the desired run-out distance. This technique does not take into account some processes involved in the landslide run-out, such as they do not directly consider that there is some energy dissipated in the remolding of the material. In this paper, a new concept was introduced, in which the rheological parameters of the material as measured in the laboratory are used, in order to reproduce the desired run-out distance. For being able to do so, the energy present in the system was lowered by the use of an Energy Reduction Factor. This new concept was applied to the Rivière Saint-Jean flowslide, where both geotechnical experiments and rheological experiments were also performed. Using a yield strength that is consistent with the material involved in the landslide, the model was able to reproduce the correct run-out distance. For doing so, the energy reduction factor had to be set to about 0.066. By using the destructuration index, which uses the geotechnical properties of the material, it was shown that approximately 45 percent of the energy was needed to remold the material, meaning an energy reduction factor of 0.55. This inconsistency between the numerical modeling results and geotechnical properties of the clay will need to be addressed by more laboratory experiments, but this new way of doing the run-out modeling seems to be a good start to integrate the in situ rheological data and geotechnical data into the modeling, which will be necessary in order to be able to assess the risk of landslide hazards, without using empirical values.

ACKNOWLEDGEMENTS

This work was financed by the Plan d'action 2013-2020 sur les changements climatiques (PACC 2013-2020) and by the Fonds vert for a financial contribution of 128 270 $. We would also like to acknowledge MTMDET who provided access to their LiDAR data as well as to soil samples.

REFERENCES

Deshpande, S.S., Anumolu, L., and Trujillo, M.F., 2012, Evaluating the performance of the two-phase flow solver interFoam, *Computational Science & Discovery*, 5: 37 p.

Flon, P., 1982, Énergie de remaniement et regression des coulees d'argiles, M.Sc. thesis, Department of civil engineering, Laval University, Quebec, Canada.

Leroueil, S., Vaunat, J., Picarelli, L., Locat, J., Faure, R., and Lee, H., 1996, A geotechnical characterisation of slope movements, in Proceedings of the 7th symposium on landslides, Trondheim, 1: 53-74.

Locat, J., 1997, Normalized rheological bejaviour of fine muds and their flow properties in a pseudoplastic regime, Proceedings of the 1st international conference on debris-flow hazards mitigation, ASCE, pp. 260-269.

Locat, J. and Demers, D., 1988, Viscosity, yield stress, remolded strength, and liquidity index relationships for sensitive clays, Canadian Geotechnical Journal, 25(4): 799-806.

Locat, J., Turmel, D., Locat, P., Therrien, J., and Létourneau, M., 2017, The 1908 disaster of Notre-Dame-de-la-Salette, Québec, Canada: Analysis of the landslide and tsunami, in Thakur V, L'Heureux J-S, Locat A (eds) Landslides in sensitive clays. From research to implementation. Springer, Dordrecht.

Locat, P., Leroueil, S., and Locat, J., 2008, Remaniement et mobilité des debris de glissements de terrain dans les argiles sensibles de l'Est du Canada, in Compte-rendu de la 4è conférence canadienne sur les géorisques : des causes à la gestion, pp. 97-106.

Turmel, D., Locat, J., and Locat, A., 2017a, Projet coulées : analyse et modélisation de la propagation des débris de coulées argileuses non confinées, rapport final LERN-Coulées-2017-01, 213 pp.

Turmel, D., Locat, J., Locat, P., and Demers, D., 2017b, Parametric analysis of the mobility of debris from flow slides in sensitive clays, in Thakur V, L'Heureux J-S, Locat A (eds) Landslides in sensitive clays. From research to implementation. Springer, Dordrecht, 301-310.

Vaunat, J. and Leroueil, S., 2002, Analysis of post-failure slope movements within the framework of hazard and risk analysis, *Natural Hazards*, 26: 83-109.

Weller, H.G., Tabor, G., Jasak, H., and Fureby, C., 1998, A tensorial approach to computational continuum mechanics using object-oriented techniques, *Computers in physics*, 12(6): 620-631.

Yong, R.N. and Tang, K.Y., 1983, Soil remolding and sensitivity measurements, *Geotechnical testing journal*, 6(2): 73-80.