

The energy reduction factor for flowslides: a new parameter to assess the energy used for landslide-tsunami initiation

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ABSTRACT

Tsunami waves are generally produced either by the displacement of a fault when an earthquake occurs or by the movement of soils caused by an underwater landslide. Sometimes, landslides that originate inland will reach a body of water in their runout zone and may create a tsunami wave, also called impulse wave. This type of tsunami initiator is considered in this paper, more precisely flowslides in sensitive clays that reach a body of water. In the generation of tsunami waves, different factors from the landslide itself must be considered, such as the velocity of the landslide when it reaches the water body and its thickness. These parameters have to be obtained analytically or by using numerical modeling.

Most studies on landslide mobility use a conventional approach based on apparent rheological properties calibrated in order to back-calculate the behavior of flowslides. However, apparent rheological properties are not the same as the rheological properties of the material as measured in the lab. This difference is attributed to the energy loss in remolding, which is not directly taken into account when using the conventional approach. In this paper, a new factor, using the destructuration index concept, is introduced in order to take into account the energy required to remold the material: the Energy Reduction factor (F_{ER}). In modeling the runout simulation it provides a more realistic simulation of the runout behavior. This factor was determined for a sensitive clay flowslide which took place in Quebec. For the flowslide studied here, the use of this factor reduces the maximum velocity of the landslide by a factor of 3.5, which will decrease the initial tsunami wave height by a 2.4 factor.

RÉSUMÉ

Les vagues de tsunami sont généralement produites soit par le déplacement d'une faille lors d'un séisme, soit par le mouvement des sols provoqué par un glissement de terrain sous-marin. Parfois, les glissements de terrain à l'intérieur des terres peuvent atteindre un plan d'eau dans leur zone de parcours et peuvent ainsi créer une vague de tsunami. Dans cet article, nous ne considérerons que ce type de glissement de terrain, plus précisément les coulées argileuses atteignant un plan d'eau. Lors de la génération des vagues de tsunami, différents facteurs liés au glissement de terrain doivent être pris en compte, tels que la vitesse du glissement de terrain lorsqu'il atteint la masse d'eau et son épaisseur. Ces paramètres doivent être obtenus analytiquement ou en utilisant une modélisation numérique.

La plupart des études sur la mobilité des glissements de terrain utilisent une approche conventionnelle basée sur des propriétés rhéologiques apparentes calibrées afin de calculer à rebours le parcours des glissements de terrain. Cependant, les propriétés rhéologiques apparentes ne sont pas les mêmes que les propriétés rhéologiques mesurées en laboratoire. Cette différence est attribuée à la perte d'énergie lors du remaniement, qui n'est pas prise en compte lors de l'utilisation de l'approche conventionnelle. Dans cet article, un nouveau facteur, le facteur de réduction d'énergie (F_{ER}), est introduit, utilisant le concept d'indice de destructuration, afin d'estimer l'énergie nécessaire au remaniement des matériaux, fournissant ainsi une estimation plus réaliste du comportement à la fin du parcours. Ce facteur est appliqué sur un glissement de terrain dans les argiles sensibles qui a eu lieu au Québec. Pour le glissement étudié ici, l'utilisation de ce facteur réduit la vitesse maximale du glissement de terrain d'un facteur 3.5, diminuant ainsi la hauteur de vague initiale d'un facteur 2.4.

1 INTRODUCTION

Tsunami waves are often caused by seism, where tectonic plates at the bottom of the ocean move masses of water. However, an important source of tsunamis are landslides that may have their origin underwater or not. Indeed, inland landslides usually pose two threats, i.e. 1) the possibility that population is affected by the retrogression part of the sliding event and 2) possibility that the population is affected by the landslide debris. However, when debris reaches a water body, tsunami waves may be generated, and the population might be at risk by this indirect consequence. Such landslide in the past includes Vajont landslide (1963), for which the

tsunami wave, that overtopped a dam, caused 1910 deaths and the destruction of villages (Muller, 1964). In Canada, the 1908 Notre-Dame de la Salette landslide was also destructive, with a death toll of 33 persons, the tsunami itself being the cause of 26 casualties (Ells, 1908, Locat et al., 2017). This Notre-Dame de la Salette landslide is the deadliest event in quick clays in Canada. This landslide was a sensitive clay flowslide, which can be defined as a succession of rotational slides (Hung et al., 2014). This type of landslide will be the principal subject of this paper, but the methodology discussed here could also be potentially used for other types of landslides in cohesive soils.

Common methods to assess tsunami hazards associated with landslides include the use of physical models to reproduce the landslide and the tsunami (Fritz, 2002), as well as numerical models (Watts et al., 2003) or empirical relationships derived from physical or numerical models (Heller and Hager, 2010). Such empirical relations includes, for aerial landslides that enter body of water, relations based on the impulse product parameter P , developed by Heller and Hager (2010). This impulse product parameter was developed using statistics over 430 different physical experiments presented by Fritz (2002), Zweifel (2004) and Heller and Hager (2010). Using the P parameter, multiple wave parameters can be estimated. The P parameter is defined as:

$$P = FS^{1/2}M^{1/4} \left\{ \cos \frac{6}{7} \alpha \right\}^{1/2} \quad [1]$$

where F is the landslide Froude number defined as [2], S the relative slide thickness ($S = s/h$) and M is the relative slide mass [3]. In these different equations, α is the hill slope angle, V_s is the slide impact velocity, g the gravitational acceleration, h the still water depth, s the slide thickness, m_s the slide mass, ρ_w the water density, ρ_s the bulk slide density and b_s the slide width.

$$F = \frac{V_s}{(gh)^{1/2}} \quad [2]$$

$$M = \frac{m_s}{\rho_w b_s h^2} \quad [3]$$

From Equations 1–3, it can be seen that in order to characterize landslide tsunami, one must be able to compute the velocity of the landslide when it reaches the water body, its mass, its thickness, and its width. The other parameters are related to the body of water. Using the P parameter, multiple wave parameters such as maximum wave height (H_M), maximum period, etc. can be computed, as described in Heller and Hager (2010, 2014) or Heller and Spinneken (2013). As an example, the maximum wave height at the impact location is defined as (Heller and Hager, 2010):

$$H_M = \frac{5}{9} P^{4/5} h \quad [4]$$

From Equation 1, it can be seen that one of the most important parameters to define the wave characteristics is the velocity of the landslide as well as its thickness. In this paper, we will first consider landslide runout modeling of sensitive clays flowslides, and then demonstrate the impact of different parameters on the tsunami initiation. For doing so, the first portion of this paper will be about the numerical modeling of sensitive clay flowslide. Then, a description as well as results for the 1983 Desbiens landslide simulation (Figure 1, Locat et al., 2008), will be presented and discussed.

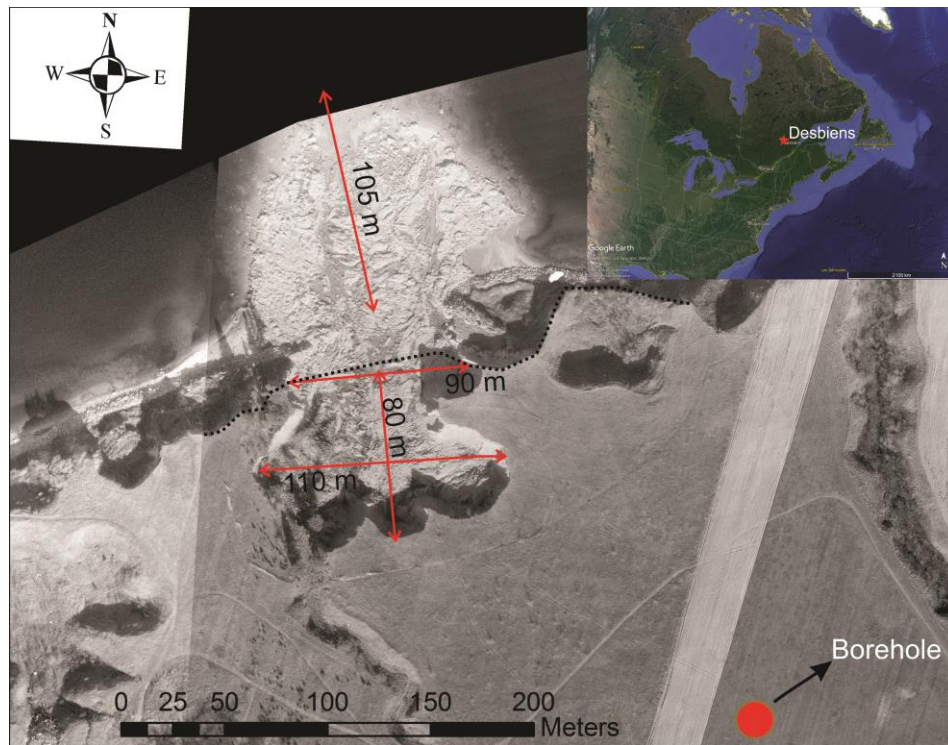


Figure 1. General morphological characteristics of the Desbiens Landslide, with the location of the borehole. The dashed line represent the approximate contour of the slope before the landslide.

2 SIMULATION OF FLOWSLIDES IN SENSITIVE CLAYS

Flowslides in sensitive clays are caused by a succession of rotational failures. For each rotational failure, the material will be remolded due to the movement of the slice. When remolded, sensitive clays show a drastic decrease in shear strength, and, if the liquidity index is high enough, the shear strength will become so low that the remolded material involved in the landslide may flow out of the crater as a viscous fluid. Using rheometers, the rheological behavior of sensitive clays have been described by numerous authors (Locat and Demers, 1988, Perret et al., 1996, Locat, 1997, Jeong et al., 2010, Grue et al., 2017) as showing Bingham ($n = 1$) or Herschel-Bulkley ($n \neq 1$) behaviors (Eq. 5). Using the simpler Bingham rheological model, the yield strength (τ_0) of remolded sensitive clays can be described as a function of the liquidity index (I_L) of the material (Eq. 6, Locat et al., 1997).

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

$$\tau_0 = \left(\frac{5.81}{I_L}\right)^{4.55} \quad (\text{for } 0 \text{ g/L salinities}) \quad [6]$$

where k is the consistency index that is equal to the viscosity for a Bingham fluid, $\dot{\gamma}$ is the shear rate and n the flow index.

However, remolding sensitive clays requires a lot of energy, that energy being provided by the potential energy of the landslide. The potential energy used to remold the material will then not be available to be transferred as kinetic energy, and therefore won't be available for movement.

It was demonstrated by Locat et al. (2008), using data from Flon (1982), Tavenas et al. (1983) and Yong et al. (1983), and a methodology similar to the one used by Leroueil et al. (1996), that to remold sensitive clays, the amount of energy required by unit volume (E_r) is a function of the plasticity index (I_p) and the intact undrained shear strength (s_u) such as, for 100% remolding :

$$E_{r100} = 16 s_u I_p \quad [7]$$

For a complete remolding, the required energy can be compared to the available potential energy by the following destructuration index (Locat et al., 2008):

$$I_D = \frac{\rho g H_g}{16 s_u I_p} \quad [8]$$

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, g the gravitational acceleration and ρ the volumetric mass density of the clay.

From a numerical point of view, this energy required to remold the debris needs to be removed from the system if

one wants to be able to use rheological data from the soils in the runout modeling rather than calibrated parameters as mentioned above. As demonstrated by Turmel et al. (submitted), the energy available for mobility (E_{AM}) will be a function of the total potential energy (E_p). This function being the energy reduction factor (F_{ER}) :

$$F_{ER} = \frac{E_p - E_{r100}}{E_p} = \frac{\rho g H_g - E_{r100}}{\rho g H_g} = \frac{\rho g H_g - 16 s_u I_p}{\rho g H_g} \quad [9]$$

As in prospective analysis, the final height of the debris is unknown, H_g can be considered as half the height of the slope. The available energy becomes:

$$E_{AM} = F_{ER} \times E_p \quad [10]$$

The energy reduction factor can be included in numerical models able to simulate the propagation of debris from flowslides, using rheologies such as Bingham, or Herschel-Bulkley. This is done, in a simplified way, by multiplying the gravitational acceleration by F_{ER} .

For the runout modeling of the Desbiens 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. *r.massmov* 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. The *r.massmov* model allows the simulation of the landslide debris runout over complex topography. For doing so, this model solves, in a Eulerian approach, Navier-Stokes equations with a shallow water assumption, i.e. solving Saint-Venant equations. Different rheological model can be simulated in the *r.massmov* software, such as the Bingham model that is used to describe remolded sensitive clays behavior. 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 landslide is not in a state of static equilibrium at the beginning of the simulations and that the rupture is not modeled; only the post-failure is modeled. Furthermore, 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. However, the *r.massmov* model allows to take 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 1983 DESBIENS FLOWSLIDE

Many flowslides did occur in the last century on the South shore of the Lac Saint-Jean, near the small town of Desbiens, which is located 185 km North of Quebec city. Among them, the 1983 flowslide will be modeled in this paper (Fig. 1). In this area, aerial photographs were acquired before the landslide in 1981, as well as the same year as the landslide.

The height of the slope before the landslide was about 13.5 m. Aerial photographs analysis suggests that the rupture surface was at the level of Lac St-jean. This landslide has a maximum width of about 110 m. It has the form of a funnel: at the top of the slope, the width is 90 m, and the minimum width is about 70 m. This landslide shows a retrogression distance of about 80 m and a runout distance of nearly 105 m. It should be noted that the furthest part of the debris is not visible on the available topographic or photographic data, so the distance could be slightly higher. The average thickness of debris on the beach is of the order of 2 m.

It is possible for this landslide to directly calculate the volume of material displaced within the scar, by subtracting the topography of 1983 to the topography of 1981. The minimum volume calculated is 66 500 m³. Considering that ~20% of the debris remains in the scar in sensitive clay flowslides (Demers et al., 2014), a total volume of ~80 000 m³ will be considered for this landslide.

The geotechnical profile from the borehole located in Figure 1 is presented in Figure 2. At Desbiens, there is a 2 m thick sand layer at the surface. Under this layer is a deposit of clay and silt with small centimetric beds of sand. Samples taken at depths of 6 and 7.5 m show plasticity indices of 36 % and 30 % respectively, these indices are found to be greatly reduced downhole, showing a value of 10 % at 9 m, 2 % at 11 m and 4 % at 14 m. The mean plasticity index for the samples above the surface of rupture is 16.4 %. The failure surface, if considered to be at the elevation of Lac Saint-Jean, would be at a depth of 14.5 m on this borehole (which is located behind the back scarp). The liquidity indices are of the order of unity between 6 and 8 m deep, reaching a maximum value of 17 at a depth of 11 m deep. The shear strength of the intact material shows maximum values in the range of around 80 kPa at depths of 3-4 m to reach a minimum of about 30 kPa at depths of 13 m, then the values are increasing. The mean undrained shear strength for samples above the surface of rupture is of 43 kPa.

Taking into consideration the mean geotechnical and morphological values, we can use Eq. 9 to calculate the proportion of the potential energy that will be used to remold the debris and use that information as an input to the numerical model. This leads to a F_{ER} value of 0.05, i.e. that 95% of the total potential energy is used to remold the material, where only 5% of the potential energy can be transferred as kinetic energy considering that all the material is completely remolded.

As the slide impact angle (a few degrees as the beach angle is quite low) is not in the range where impulse product parameter are typically tested (i.e. between 30 and 90 degrees), the wave height produced by the

different scenarios won't be calculated here. However, to be able to illustrate the impact of the different analysis on the wave height, the following hypothesis will be made: the impact with the water will be after a runout distance of 20 m. Furthermore, a water depth of 2 m will be considered.

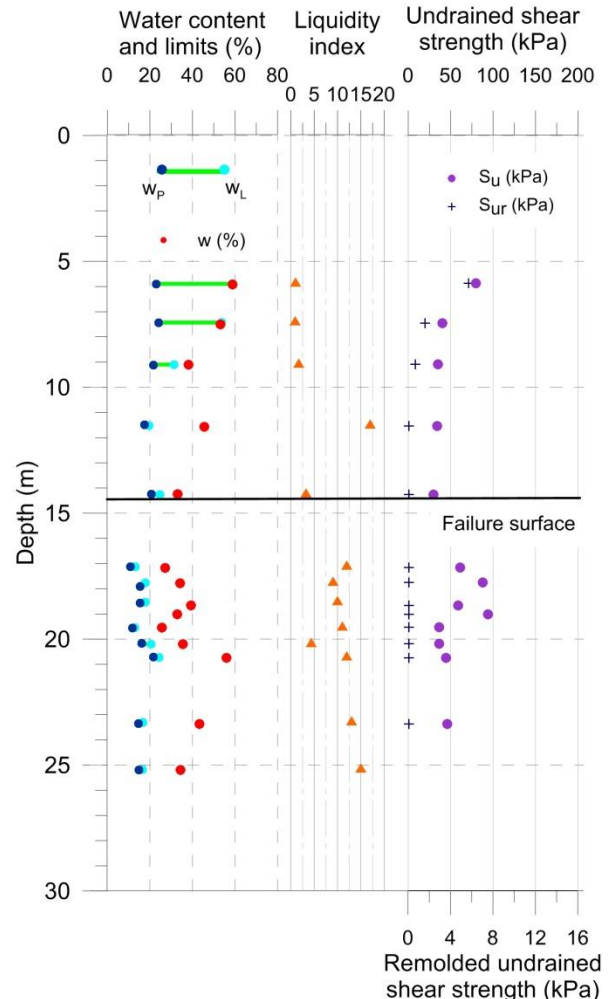


Figure 2: Geotechnical profile for the borehole located on Fig. 1.

4 NUMERICAL MODELING

Many simulations were conducted to back-calculate the debris runout for the Desbiens landslide. Two types of simulations were performed, i.e. (1) the conventional simulation where rheological characteristics of the sensitive clays were varied to obtain the proper runout distance and (2) simulations where the F_{ER} calculated with the mean geotechnical characteristics was imposed, and then the yield strength and viscosity were varied in order to obtain the proper runout distance. These two types of simulation then differ by the use of the F_{ER} , which limits the available energy in the system in order to take into account energy used to remold the material. In this section, results from these two types of simulations will be

presented, as well as their impact on the impulse product parameter. In all the analysis, the viscosity is set to be 1:1000 of the yield strength, as it is the value generally observed in sensitive clays (Locat 1997). The viscosity being orders of magnitude lower than the yield strength it does not play a preponderant role in the runout behavior of sensitive clays when compared to the yield strength.

In the conventional analysis, in order to reach a runout distance of 105 m, a yield strength of 2800 Pa is necessary (Fig. 3). The velocity profile for the frontal element obtained using for this simulation is shown in Fig. 4. That shows a strong acceleration up to a velocity of 7.6 m/s, after a displacement of 16 m, followed by a deceleration that will lead to the halt of the landslide after 28 seconds. The thickness of the debris after 20 m of movement is shown in Fig. 5a. It can be seen that the whole retrogression movement is not completed on this figure. At the front of the landslide, the mean thickness of the debris is around 2.6 m.

When the F_{ER} of 0.05 is considered, the yield strength necessary to obtain the runout distance of 105 m is 130 Pa (Fig. 6) which is much less than what has been obtained with the conventional approach. Using Eq. 6, this yield strength value would correspond to a deposit with a mean liquidity index of 2, which is reasonable when taking into consideration the different liquidity index seen in the geotechnical profile. The velocity profile obtained from this analysis is also shown in Fig. 4. The maximum velocity reached from this simulation is 2.2 m/s, that is reached after 15 s or a movement of the frontal element of 20 m. The thickness of the debris after 20 meters of displacement is shown in Fig. 5b. At the front of the landslide, the mean thickness is around 2.1 m. The whole movement lasts longer than with the conventional simulation, i.e. around 90 s.

A comparison of the two analyses shows a maximum velocity, for the same runout distance, that varies between 2.2 and 7.6 m/s. After a runout distance of 20 m, which corresponds to the hypothesis that the landslide will hit the water after 20 m, the velocity of the conventional analysis will be of 7.4 m/s. At the front of the landslide after a movement of 20 m, the analysis with the F_{ER} leads to a flowslide thickness 0.5 m higher than for the conventional analysis (2.6 m vs 2.1 m). Using Eq. 2 to estimate the landslide Froude number, it can be shown that the landslide Froude number will be 3.4 times higher with the conventional analysis (1.74) than with the F_{ER} analysis (0.52). The relative slide thickness will be similar, with a value of 1.3 for the F_{ER} analysis and 1.05 for the conventional analysis. Considering that the other parameters will be the same for the two analyses, it can be shown using equation 2 that the combined effect leads to an F value three times higher in the case of the conventional analysis than in the analysis using F_{ER} .

From equation 4, it is possible to conclude that the maximum wave height modeled with the conventional analysis will be 2.4 times higher than with the analysis made with the F_{ER} .

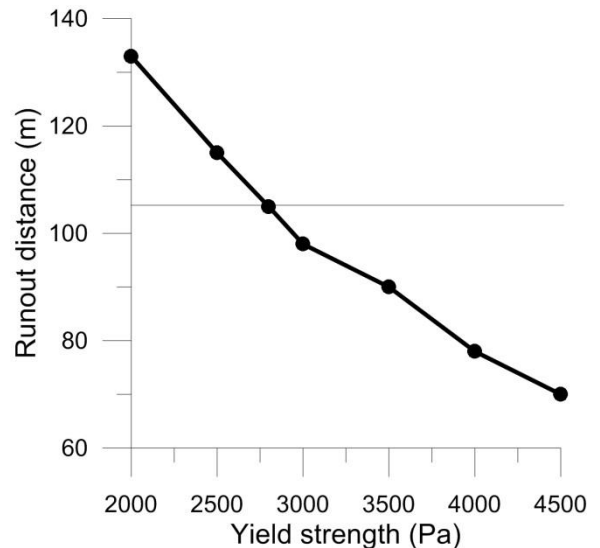


Figure 3: Effect of the yield strength on the runout distance for the conventional analysis

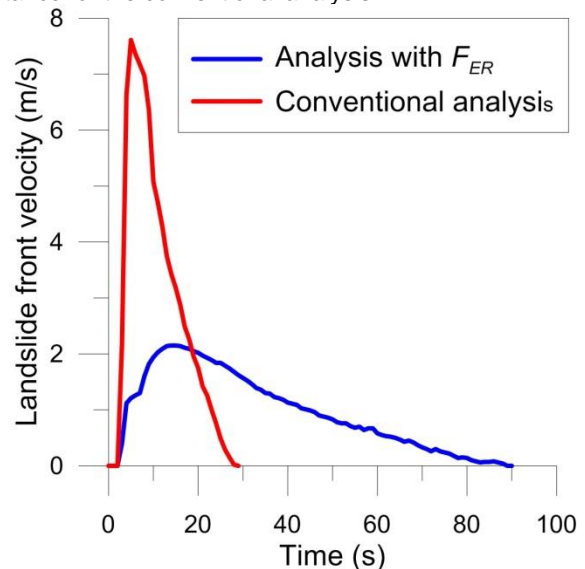


Figure 4: Velocity profile for the frontal element for the conventional analysis and the analysis with F_{ER}

5 CONCLUDING REMARKS

The tsunami caused by inland landslides hitting a body of water is controlled by the thickness of the landslide, its width and more importantly its velocity when it reaches the water body. Conventional analysis of landslide in cohesive materials generally does not take into account that in order to flow, the material must undergo a transformation from an intact to a remolded state. In many instances, this requires a lot of energy, and that energy will not be available as kinetic energy. The conventional approach ignores this transformation by using an apparent yield strength, unrelated to the yield strength as measured in the laboratory. By doing so, the anticipated velocities of the landslide are not coherent with the physics of the landslide. Hence, the Energy Reduction

Factor (F_{ER}) has been introduced in the numerical approach, a parameter that takes into account the quantity of energy required to remold the debris. This energy can be estimated with usual geotechnical parameters. In the case of the Desbiens landslide modeled in this paper, it was found that the use of conventional simulation will lead to maximum velocities almost four times higher than with the simulation using reduced potential energy calculated with the energy reduction factor (F_{ER}).

Combined with the shape of the landslide that will be slightly different, this would lead to an initial wave amplitude 2.4 times higher than with the simulation using the energy reduction factor. The conventional approach clearly exaggerates the velocity as well as the initial wave height. The use of the Energy Reduction Factor helps to better calibrate tsunami models in the initiation phase, when a landslide in cohesive materials reach water bodies in their first instants, by a better description of the initial acceleration of the landslide mass.

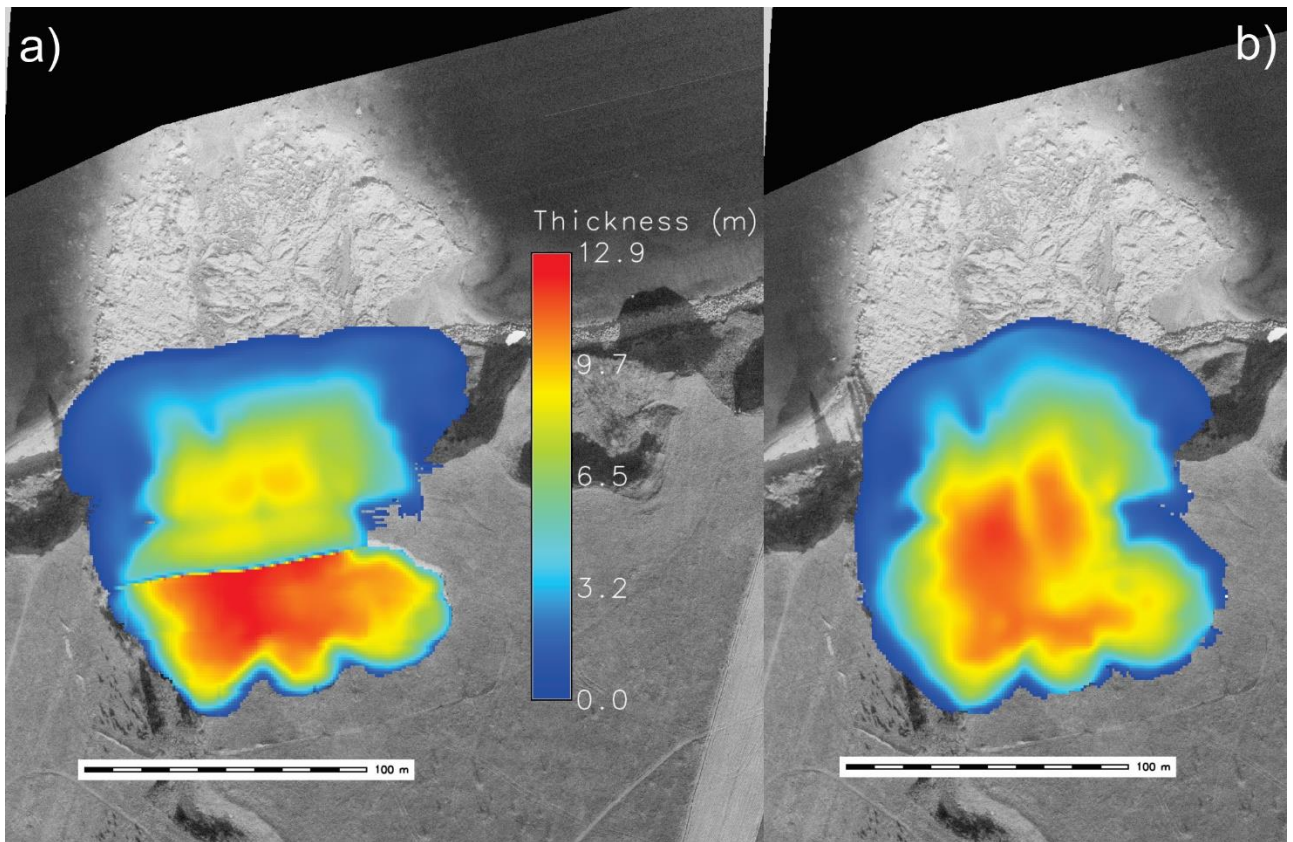


Figure 5. Thickness of the debris after a runout distance of 20 m, for the conventional analysis (a) and the analysis using the F_{ER} (b).

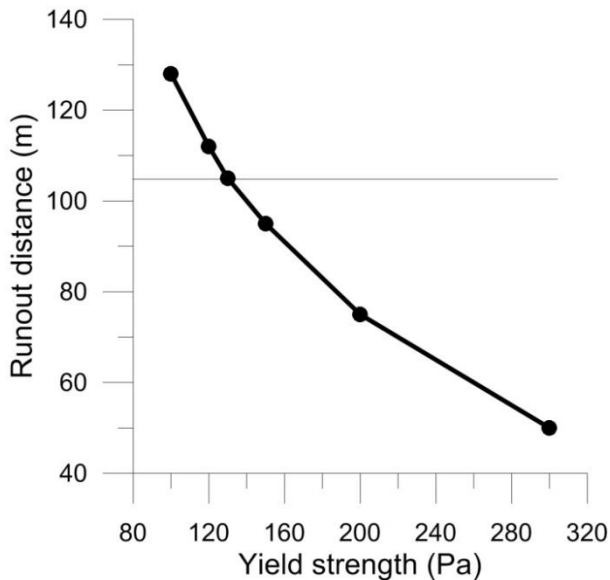


Figure 6: Effect of the yield strength on the runout distance for the simulation using the F_{ER} . The horizontal line represents the estimated run out distance for the Desbiens flowslide at 105 m.

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