Empirical estimation of the retrogression and the runout distance of sensitive clay flowslides

Dominique Turmel[1], Janelle Potvin[2], Denis Demers[2], Pascal Locat[2], Ariane Locat[3], Jacques Locat[1], Serge Leroueil[3]
[1]*Département de géologie et de génie géologique, Université Laval, Québec, Québec, Canada*
[2]*Ministère des Transports, de la Mobilité durable et de l'électrification des transports, Québec, Québec, Canada*
[3]*Département de génie civil et de génie des eaux, Université Laval, Québec, Québec, Canada*

ABSTRACT
In order to assess the landslide hazard in sensitive clays, two different parameters must be evaluated: the retrogression distance of the landslide and the runout distance of the debris. This is particularly important for sensitive clay flowslides where retrogression and runout distances may reach hundreds of meters, even in relatively flat terrains. Up to now, the retrogression and the runout distance of these landslides were estimated mostly using empirical relationships. In this paper, the methodology developed by the Quebec Ministry of Transportation (MTMDET) in Quebec province, Canada, is summarized. Following this, a comparison is made between MTMDET procedure and the methodology developed in Norway, another country where sensitive clay flowslides are commonly seen. Finally, these procedures are applied on two different cases in Québec, where both the retrogression and runout distances are known, to show the differences between these two methodologies.

RÉSUMÉ
Afin d'évaluer les zones pouvant être touchées par les glissements de terrain dans les argiles sensibles, deux paramètres doivent être évalués : la distance de rétrogression du glissement ainsi que la distance de parcours des débris. Ces paramètres sont particulièrement importants pour les coulées argileuses, où la distance de rétrogression et la distance de parcours peuvent atteindre des centaines de mètres, et ce même dans des terrains relativement plats. Jusqu'à maintenant, la rétrogression et la distance de propagation de ces glissements ont été estimées principalement en utilisant des relations empiriques. Dans cet article, la méthodologie développée par le ministère des Transports du Québec (MTMDET) Canada, est présentée. Suite à cela, une comparaison est faite entre la procédure MTMDET et la méthodologie développée en Norvège, autre pays où ces types de glissement sont couramment observés. Enfin, ces procédures sont appliquées dans deux cas au Québec où les distances de rétrogression et de propagation des débris sont connues, pour montrer les différences entre ces deux méthodologies.

1 INTRODUCTION

Landslides in sensitive clays are common in Eastern Canada, in some raised fjords deposits in Western Canada as well as in Scandinavian countries such as in Norway. Most of these landslides will exhibit a retrogression distance of less than twice the height of the slope. However, some landslides, such as lateral spread failures and flowslides, may develop retrogression distances of hundreds of meters (figure 1). These landslides poses two threats to the populations: the first one is the possibility that the infrastructures constructed over prone areas are affected by such landslides; the second threat is that the infrastructures are in areas that may be damaged by debris from these landslides. Debris from flowslides may travel hundreds of meters, and even kilometers when channelized.

In order to assess sensitive clay flowslide hazards, these two parameters, i.e. the retrogression distance and the runout distance of the debris, must be evaluated. In Québec and Norway, these two parameters are mostly evaluated using empirical relationships, with the help of the geotechnical properties of the material or using geometrical informations.

After a short review of flowslides in sensitive clays and the different factors that may play a role in their retrogression and propagation, the different methodologies for retrogression and runout distance estimation developed in Norway in the last years, will be briefly summarized. The methodology used in Quebec province will then be explained in more details. Finally, a comparison on these different methods on two real cases in Quebec will be made.

2 FLOWSLIDES IN SENSITIVE CLAYS

Relatively low runout and retrogression distances are observed in most landslides in sensitive clays. However, in some instances, after a first rotational landslide, a succession of rotational landslides may develop. This kind of process, also called flowslide, may affect hectares of lands, and is characteristics of areas that contains sensitive clays.

In general, at least two conditions are necessary in order to have a first rotational landslide to develop into a flowslide. The first condition is that the height of the backscarp must be high enough that the potential energy of the debris is large enough to remould the debris (e.g. Tavenas et al., 1983). Secondly, the debris consistency must flow as a liquid, in order to be able to exit the crater area (a liquidity index larger than 1.2 or a remolded shear strength of less than 1 kPa are proposed by Lebuis et al. 1983 for eastern Canada).

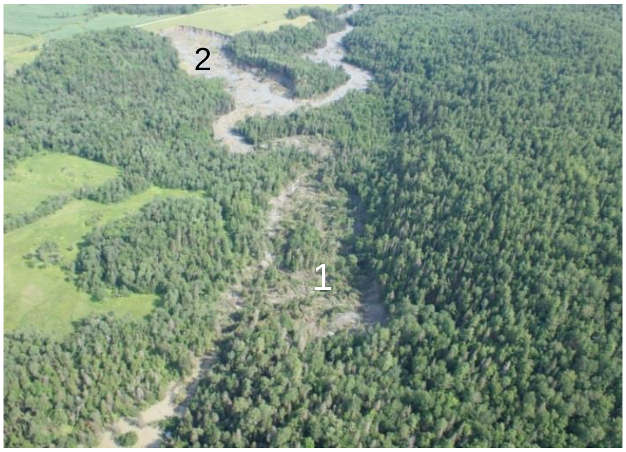

Fig. 1: View of two major retrogressive landslides along the l'Argile river in 2010, Notre-Dame-de-la-Salette. The number one was stopped by rock outcrops.

From a geotechnical point of view, Mitchell and Markell (1974) proposed that this retrogression can only occur if the stability number (N_s, eq. 1) is greater than 6 for flowslides in Eastern Canada.

$$N_s = \frac{\gamma H}{s_u} \quad [1]$$

Where γ is the bulk unit weight of the soil, *H* the slope height and s_u the undrained shear strength of the soil.

However, in a more recent version of his study, Mitchell (1978) mentioned that their previous conclusions did not apply in very stiff silts and clays outcropping in the eastern part of Quebec, where large landslides can occur even when the stability number N_s is quite low. Indeed, Demers et al. (2014) showed that many historical and ancient flowslides that occurred in Quebec had $3 < Ns < 5$, some having retrogression of several hundred meters. Nevertheless, Geertsema and L'Heureux (2014) mention that this threshold is likely higher than 6 in Norway, where clays are generally softer than in Quebec.

To the author's knowledge, Mitchell and Markell (1974) were the first to propose an empirical relationship in order to estimate the distance of retrogression. This relationship (eq. 2) proposes that for sensitivities greater than 10, the distance of retrogression (*R*) can be correlated to the stability number.

$$R = 100(N_s - 4) \quad [2]$$

Other methodologies were also proposed (Carson, 1979; Quinn, 2011) some using geometrical constraints, for example by Carson and Lajoie (1981). However, as concluded by Demers et al. (2014), none of these previous methods gives satisfactory predictions in Quebec's conditions.

As exemplified by the conditions necessary to develop flowslides, factors that will influence retrogression as well as runout distance of sensitive clay flowslides can be classified in two different categories: material parameters and geometrical parameters. Geertsema and L'Heureux (2014) did a thorough review of these different factors, and conclude that geometric parameters include slope and orientation of the ground surface as well as the bedding plane, the geometry of the valley, the depth of the failure surface and finally the presence and localization of bounding streams. Material specific factors include the intact and remolded undrained shear strength, the sensitivity and the stability number.

Up to recently, empirical relationships for the estimation of the runout distance of these landslides were absent in the literature. From statistical analysis, Locat et al. (2008) as well as L'Heureux (2012) described the relationships between retrogression distance or landslide volume with the runout distance. More recently, studies by Yifru (2017), Liu et al. (2017) Turmel et al. (2017a, b) or Locat et al. (2017) aim at using numerical modeling in order to calculate the runout extent of debris from sensitive clays flowslides.

3 SUMMARY OF THE GEOLOGICAL CONTEXT

Sensitive clays in Norway and Eastern Canada result essentially from the leaching of post-glacial marine clays (Rosenqvist 1953; Torrance, 2017), which were deposited about 10000 to 12000 years ago. In the geological context of Norway, marine clays were mostly deposited in ancient fjords now forming small and narrow valleys. In this context, the raised marine deposits form plains which are often slightly inclined and the extension of these soils are often limited by other glacial deposits (till, fluvioglacial sediments) or by the rock escarpments of the fjords. In Québec province, as the post-glacial marine sedimentary basins were many ten of kilometers wide, the marine clays are typically uniformly distributed in large sedimentary basins. The now emerged marine sediments form nearly flat clay plains. In addition, leached clays (sensitive clays) are also found over very large distances. In summary, the geomorphological context of Quebec is probably more favorable than in Norway to the development of flowslides having huge retrogression distances, some ancient scar showing retrogression up to 5 km.

4 NORWEGIAN METHODOLOGY

At least three different methods for the zonation of the retrogression distance were developed in Norway (fig. 2), and one method was developed for the runout distance. These methods are briefly described here, but more details are to be found in cited references.

4.1 Retrogression – 1:15 method

The method presently used by the Norwegian Water Resources and Energy Directorate (NVE) for the national mapping of hazard zones is quite simple. The maximum retrogression distance of a potential flowslide in sensitive clay is taken as the extent of a 1V:15H line drawn from the toe of the slope (Haugen et al. 2017). This empirical ratio is based on Karlsrud et al. (1984) study that concluded that the maximum retrogression distance for flowslides in quick clays is 15 times the height of the slope. However, a more recent compilation made by L'Heureux (2012) showed that some landslides in Norway have reached larger distances. Nevertheless, according to Haugen et al. (2017), this ratio is conservative, as it does not take into account the location and thickness of the sensitive clay zone.

4.2 Retrogression – NIFS method

Between 2012 and 2016, a research and development program called NIFS was funded in Norway. Part of this program was about hazard mapping, and they developed and proposed a new methodology (NIFS, 2016) to evaluate the retrogression distance of flowslides. First, they propose that a retrogressive sensitive clay slide will occur if more than 40% of the soil over the critical slip surface (first landslide) is sensitive, with a remolded shear strength of less than 1 kPa (NIFS, 2016; Haugen et al. 2017). If this first characteristic is encountered, they then establish a rating of the site that determines the retrogression distance. In that methodology, three different extents may be attained depending on that rating, i.e. 1:5, 1:10 or 1:15. This slope is drawn from the base of the critical slip surface, and not the base of the slope as the actual 1:15 method. The rating is a function of the geometry of the sensitive clay deposit, the distance where sensitive clay is encountered on the slip surface, the geometry of the runout area, the retrogression distance of historical flowslides in the area and the inverse of the stability number. Specific details on this method are given in NIFS (2016).

4.3 Retrogression – NGI method

In their studies, the Norwegian Geotechnical Institute (NGI) has used, as proposed by the NIFS, the base of the critical slip surface, and not the base of the slope, as the reference for the 1:15 line, in cases where the thickness of the sensitive clay layer, with a s_{ur} of less than 1 kPa, is limited, or drops downward away from the slope (Gregersen 2010, Haugen et al. 2017). Furthermore, when the slip surface is not anymore in sensitive clays, they are using a 1:3 to 1:2 line, depending on the soil properties and pore water pressure conditions, and not a 1:15 line as currently used in the NVE 1:15 method.

4.4 Runout distance – NIFS method

Once the retrogression distance established, the runout distance can be evaluated using empirical relationships. NIFS research recommend (Strand et al. 2017) that the runout distance (E), for flowslide in open terrain, be 1.5 times the retrogression distance. If the landslide was to happen in channelized terrain, this runout distance would be 3 times the retrogression distance.

For cartographic means, there is also necessity to evaluate the width (W_u) of the runout zone. For doing so, Strand et al. (2017) suggest two equations: for flowslides in channelized terrain:

$$W_u = \frac{D}{3D_u} \times W \qquad [3]$$

for flowslides in open terrain:

$$W_u = \frac{2D}{3D_u} \times W \qquad [4]$$

In eqs. 3 and 4, W and W_u represent respectively the maximum width of the crater and the maximum width of the debris, and D and D_u represent respectively the depth of the sliding surface from the natural terrain and the average thickness of the debris. In these equations, the variables concerning the landslide itself should be known. However, there are two unknowns, i.e. the width of the debris, and the average thickness of the debris. According to Strand et al. (2017), these values must be obtained incrementally, considering that the initial volume and the volume of the debris must correspond. Informations from historical landslides in the area should be used in order to estimate these values (Strand et al. 2017).

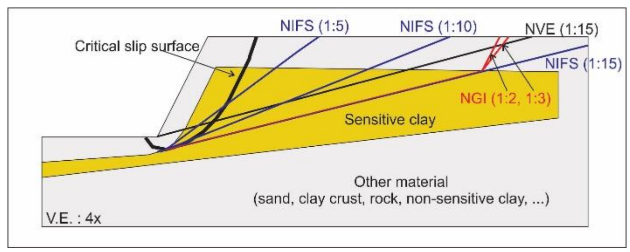

Fig.2: Empirical relations used in Norway in order to estimate the retrogression distance.

5 MTMDET METHODOLOGY

5.1 Retrogression distance

The analysis of many historical cases of flowslides in Quebec shows that the process of retrogression stopped without any geotechnical or geometric constraints. So, in order to estimate the retrogression distance (R) of retrogressive landslides, the MTMDET is using the statistical method mentioned by Lebuis et al. (1983) and described in details in Rissmann et al. (1985). This method has been used in the first surveys made in the 80's, and is still in use today. Broadly speaking, when geotechnical and geomorphological conditions are met in a potential site, the retrogression distance is evaluated using a third order moving average of the retrogression distance of historic scars in the area. In order to determine this moving average along a watershed, only the most important and representative retrogressions are kept in the model (fig. 3). Flowslides where the extension was limited by topographic depressions, such as ravines or older scar, or where a stratigraphic change is apparent, such as when the rock comes closer to the surface, will also be discarded from the analysis. This approach is based on two main considerations. The first is that the retrogression distances of the old, highly retrogressive landslides are the result of the integration of all existing conditions in a sector and as such can be considered as "life-size tests". The second hypothesis is that sites with similar properties and conditions will produce landslides in the future with retrogression distances similar to old scars. The retrogression distances thus determined are applied according to the specific conditions encountered at each potential initiation zone. Natural obstacles or change in stratigraphic conditions, as mentioned above, are taken into account where appropriate.

There is therefore no limiting value to the anticipated retrogression distance, except those related to the observed maximum values or natural obstacles. As for the potential width (W) of future events, this is also determined empirically, based on the average W / R ratio for the scars of the sector. Finally, using the anticipated retrogression at a given location, from a graph like that of Figure 3, and the W / R ratio specific to the region, it is possible to delimit the dimensions of the areas that can be affected by a highly retrogressive landslide.

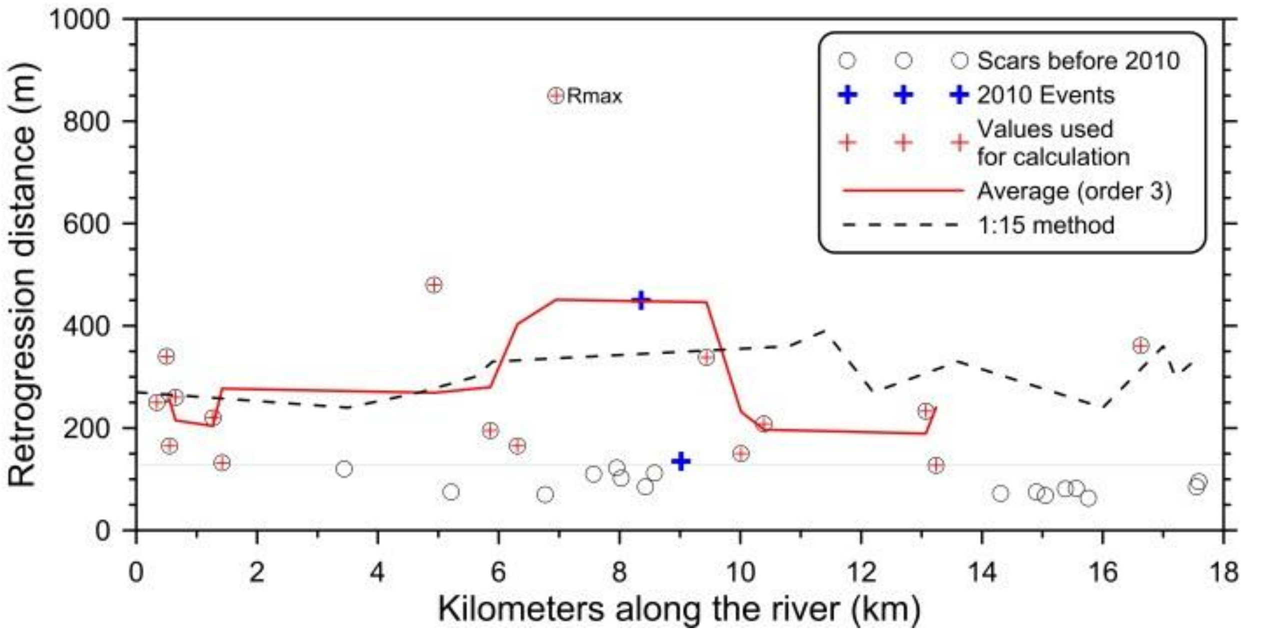

Fig.3: Retrogression distance estimated along the l'Argile river, near Notre-Dame-de-la-Salette, Québec. See figure 1 and Perret et al. (2011) for the two 2010 landslides.

5.2 Runout distance

MTMDET developed using historical events a methodology to estimate the runout distance for their cartographic needs. As it was the case for the Norwegian NIFS methodology, two different geometries must be considered: when the debris spreads out in open terrain and when the debris are channelized. A third scenario is also considered, i.e. when the flow is channelized, but the channel is not long enough in order to contain all the debris.

However, in the MTMDET methodology, the ratio between the debris mean height and the depth of the sliding surface is pre-determined. Based on CPTU soundings carried out inside many flowslide scars, this ratio is set as 0.2 (Demers et al. 2014), meaning that, from statistics on these landslides, it is determined that the mean height of the debris resting inside a flowslide scar is always approximately 20% of the height of the crater. Furthermore, their analysis considers that about 20% of the debris of a new flowslide will remains in the crater and 80% will run out of the landslide scar. In addition, it is assumed that the average thickness of debris outside the scar will be comparable to that remaining inside.

5.2.1 Runout on open-terrain

From the analysis of historical landslides, it was noticed that debris from flowslides in open-terrain take the shape of a fan, showing almost a semi-circular shape.
The area (S) of such a circular shape can be calculated as :

$$S_{debris} = 0.5 \times \pi \times E^2 \quad [5]$$

Where E is the radius of the circular shape. It is possible to isolate E such as :

$$E = \left(\frac{S_{debris}}{0.5\times\pi}\right)^{-2} \quad [6]$$

With the two hypotheses previously described, one can say that the surface of the runout zone will be four times larger than the surface of the landslide crater. Saying such, one could write:

$$S_{debris} = 4 \times S_{crater} \quad [7]$$

Where

$$S_{crater} = W \times R \quad [8]$$

Then, the radius of the circular shape is:

$$E = \left(\frac{8 \times W \times R}{\pi}\right)^{-2} \quad [9]$$

5.2.2 Runout in channelized terrain

In the case where the flow is channelized, such as a landslide that occurs on a river bank, it is hypothesized, based on historical observations, that $1/4^{th}$ of the flow will flow upstream of the landslide, and $3/4^{th}$ of the flow will flow downstream of the landslide. Knowing the surface of the crater, as well as the width of the channel, it is then possible to calculate the length of the debris. This considers that the debris won't overrun on the banks of the river, and will stay in the channel.

However, if the actual volume of the channel is not large enough to accommodate the whole volume of the debris, the debris will overrun on the banks at the end of this channel, and the remaining volume will be deposited using equations developed in 4.2.1, considering only the volume of material remaining.

6 APPLICATION

The Saguenay-Lac-St-Jean region, located approximately 200 km North of Quebec City, Québec, Canada, is an area prone to large retrogressive landslides. South of the Saint-Jean Lake, the Desbiens area was previously studied by Demers et al. (2002). Stratigraphic record in this region shows that the clay layer varies in thickness from 15 to 200 m, and this layer is overlaid by deltaic or littoral sand up to 2 m thick. In this area, the clay cliff height vary between 14 and 22 m (Demers et al. 2002), and upslope, the terrain is relatively flat.

Many landslides were noted in this area, among them five were described by Demers et al. (2002) as sensitive clay flowslides, four of them being dated between 1930 and 1983. As an example here, the 1983 landslide will be considered (Figure 4).

This landslide has a maximum width of about 110 m, but shows an irregular geometry, with a bottle-neck like shape, with a minimal width of 70 m. Retrogression distance of this landslide is about 105 m, retrogression taken here from the base of the slope. The runout distance is 110-120 m. The exact distance is unknown as the aerial photograph taken after the event does not include all the debris, and only include 105 m of runout. In this area, the slope height is 14 m. One borehole was drilled at proximity of the landslide and geotechnical results were presented by Locat et al. (2008). It shows that from a depth of 2 m to at least 30 m, the soil is composed of clay and silt, with centimetric sand layers. The top 2 meters is composed of sand. From a depth of 8 meters to the end of the boring, the clay shows very high values of liquidity index, with a plasticity index that decreases abruptly with depth, from a value of 36% at a depth of 6 m to a value of 2% at a depth of 11 m. Under 10 m depth, the remolded shear strength is extremely low.

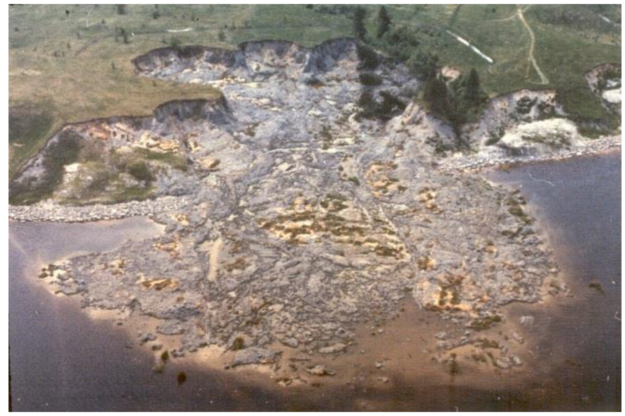

Fig. 4: The 1983 Desbiens flowslide.

6.1 Norwegian methods

As previously presented, at least three different methods are available in Norway. The simplest method is the 1:15 method, and with a mean slope height of 14 m, this method would show a maximum retrogression (R) of 210 m. The second presented method is the method proposed by NIFS (2016), which scores a slope according to different parameters. For this particular slope, even if some parameters are not possible to evaluate with only one borehole, the score obtained would be greater than 16, meaning that the slope to be used for the calculation would be a slope of 1:15, meaning that the length would be approximately the same as with the 1:15 method, the only difference would be if the critical slip surface is deeper than the lake level.

As the Desbiens site is an open terrain, the estimation of the runout distance is 1,5 times the anticipated value of the maximum retrogression, which gives a value of 315 m.

For the estimation of the width of the runout zone (equation 4), the width of the anticipated flowslide (W) was taken as the maximum distance between scars previous to the 1983 one (about 220m), as there were no indications on how to calculate the flowslide width given by Strand et al. (2017). Also, to a better comparison of the Norwegian and Quebec methods, the same assumptions were made for the depth of the sliding surface (D=14 m), corresponding to the toe of the slope, and for the average thickness of the debris (Du=0,2*14=2,8m). According to Eq. 4, the width of the debris would be 733 m. The red lines on figure 5 show the Norwegian predictions.

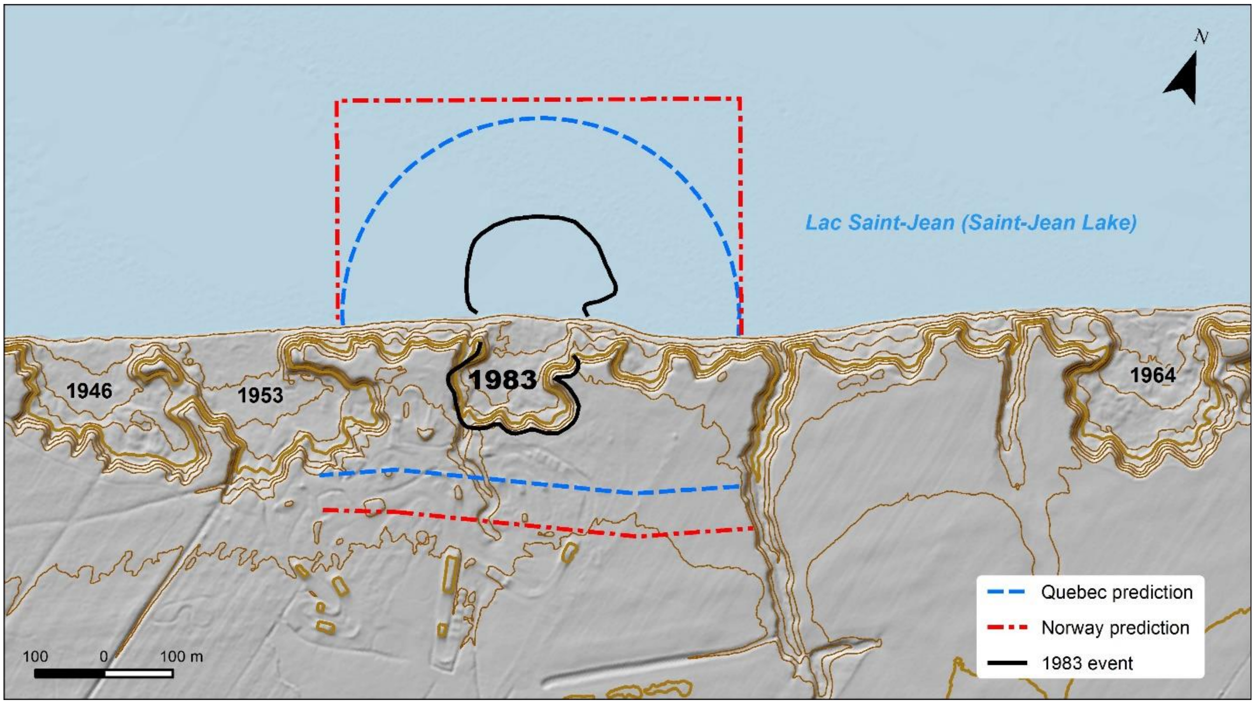

Fig. 5. Example of Desbiens

6.2 MTMDET method

The flowslide scars considered in the study for the 1983 event are those of 1946, 1953 and 1964 (figure 5). Their retrogression distances, measured in the axis motion, are respectively 160m, 150 m and 135 m. The smaller ones in the same area were not considered. Based on the 3rd order moving average of these adjacent scars, the probable retrogression distance (R) is estimated at 150 m, a slightly lower value than the one found with the Norwegian method (210 m). The value used for the W / R ratio of scars in the region is 1.5, which gives an anticipated width of 225 m, a very similar value as the Norwegian method (220 m). According to Eq. 9, as the Desbiens site is an open terrain, the maximum runout distance is estimated about to 295 m and the predicted width is then 590 m (blue lines on figure 5).

7 DISCUSSION

7.1 Norwegian methods

Different methods were developed in Norway to evaluate the retrogression distance, from quite simple ones using always a 1:15 slope, to more complex methods such as the one proposed by the NIFS program, that takes into account different parameters such as the thickness of the sensitive clay deposits, with a $c_{ur} < 1$ kPa, and the stratigraphic position of this deposit. However, even this more complex methodology has as a maximum constrain a 1:15 slope. As mentioned by L'Heureux (2012), some flowslides in Norway did present retrogression distance higher than 15 times the slope height. However, from a probabilistic point of view, these events may be quite rare in Norway. In the case of 1983 Desbiens landslide, this criterion appears to be quite conservative.

For the propagation distance, the evaluation is made using one equation that considers two unknowns, i.e. the thickness of the debris and the width of the debris. These characteristics may be estimated using the geometry of the historic landslides in the area. Here, we used the same thickness of debris as with the MTMDET method, which corresponds to the historical values in Quebec. Using these data, a maximum propagation distance of 315 meters was calculated, and considering a landslide width of 220 m, the debris width was calculated to be 733 m. If the shape of the debris is taken as a rectangle, the volume of the debris in that rectangle would be the same as the total volume of the landslide.

However, this calculation does not take into account that some debris will remain in the landslide scar. As was noticed in many flowslides in Québec, the debris thickness inside the crater is approximately the same as outside the crater. In order to be able to take into account these debris, we would have to modify eq. 3 or 4, in the sense that the value "D" would be the thickness of the deposit minus the thickness of the debris. This would lead to a debris width of 587 m in this example.

7.2 MTMDET method

In the case of 1983 Desbiens landslide, the Quebec approach for the estimation of the retrogression distance appears to be quite conservative too. This method was tested about 10 times against the cartography produced in the 1980s, when highly retrogressive landslides occurred. In all cases, the effective retrogression was equal to or less than the predictions (MTMDET, internal document).

Nevertheless, this approach raises various difficulties. On the one hand, the use of a moving average has the effect of limiting the anticipated retrogressions to values always lower than the largest recorded retrogression distance in the past (see figure 3). As example, the case of the 1993 flowslide in Lemieux, Ontario, shows the limitations of this approach, as this landslide was the largest and the youngest among seven scars along the South Nation River (Lawrence et al 1996). It is considered, however, that the probability of exceeding this statistical approach is very low, such as what is considered in Norway with their 1:15 approach.

As seen on figure 6, many flowslides in Québec did present retrogression distances higher than 15 times the slope height, some showing retrogression distances up to 50 times. Although retrogression distances greater than 15 times the slope height are rather rare, the Québec method takes into account these cases when encountered in a region, using a regional statistical approach. From this perspective, MTMDET's method seems safer in the Quebec geologic conditions. In addition, in a region where all scars would have retrogression distances well below a value of 1:15, the Quebec approach reduces overestimations of restricted lands.

On the other hand, the MTMDET method also has certain methodological limitations, including the choice of scars that are used for the calculation of the moving average, as well as the low statistical representativeness when there are only few scars in the watershed, or that one of them is very disproportionate as compared with the others for no known reason. In practice at MTMDET, these questions are always discussed by a group of specialists before making joint decisions.

8 CONCLUDING REMARKS

In the Desbiens case, the two approaches give similar results and both are conservative, particularly for the estimation of the area affected by the runout of the debris. In this case, it can be concluded that these approaches provide sufficient protection to ensure the safety of the population, in the case of future residential developments for example.

However, in the case of Notre-Dame-de-la-Salette, the estimation of the retrogression distance by the 1:15 Norwegian method gives results very different from the Quebec approach in some parts of the studied river (fig. 3). In the case of the largest of the two landslides that occurred in 2010 (the blue crosses in fig. 3), the application of the Norwegian method would have led to an underestimate of about 100 meters of the retrogression distance.

Concerning the prediction of the debris width, both approaches give similar results and seem very conservative.

It can then be concluded that both Norwegian and Quebec approaches are safe in the majority of cases. However, both consciously agree to not “cover” the worst cases that may occur, on the basis that such events are very rare. Nevertheless, the use of the 3rd order moving average method for the prediction of the retrogression distances seems better suited to the Québec geological context, because it allows for more important potential events to be taken into account. However, this statistical approach is difficult to use where there is few scars along a water course. In the latter case, the study area can sometimes be enlarged in order to have a sufficient number of data.

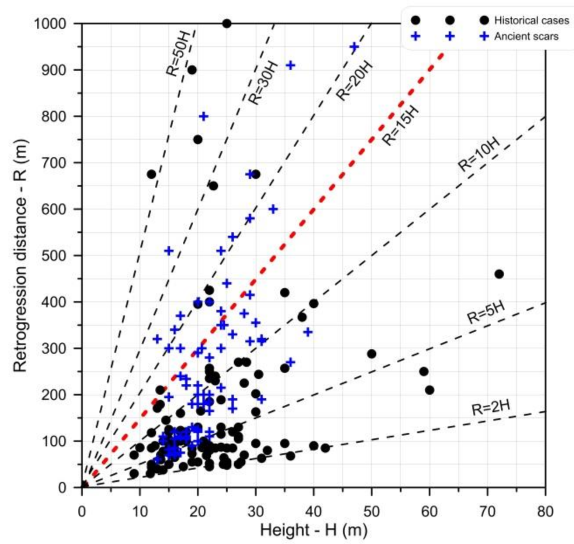

Fig.6: Relationship between R and H for Quebec cases.

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