The 1976 landslide at Saint-Fabien, Québec

Tremblay-Auger, F.,
Département de génie civil et de génie des eaux – Université Laval, Québec, Québec, Canada
Levasseur, P-P.
Golder Associates Ltd., Mississauga, Ontario, Canada
Demers, D.
Ministère des Transports, de la Mobilité Durable et de l'Électrification des Transports, Québec, Québec, Canada
Leroueil, S. & Locat, A.
Département de génie civil et de génie des eaux – Université Laval, Québec, Québec, Canada

ABSTRACT
The Saint-Fabien landslide occurred in December 1976, 270 km east of Quebec City, Canada. The landslide took place in a glacial valley filled with glaciomarine clays covered by peat bog deposits, around Road 132, while construction was going on along the road. Unique features of this event are the almost horizontal ground surface and the failure surface that also seems to be close to the horizontal. In addition, passive and active failure zones could be observed in the debris, indicating a possible downward progressive failure mechanism, unusual in Eastern Canadian clays. The geotechnical investigations of the landslide have been done by the Québec Ministry of Transportation (MTMDET). The witnesses' accounts, that can be found in the records from the lawsuit that took place after the event, also helped to understand how the landslide took place. This paper presents the description of the events and the geotechnical investigation.

RESUME
En décembre 1976, un important glissement de terrain s'est produit près de la municipalité de Saint-Fabien, à 270 km à l'est de la ville de Québec, au Canada. La zone du glissement se situe au creux d'une vallée rocheuse appalachienne partiellement rempli par des argiles sensibles recouvertes d'un dépôt de tourbe. Des travaux étaient en cours à cette période le long de la route 132 traversant la zone du glissement. La surface du sol, ainsi que la surface de rupture sont pratiquement horizontales, ce qui en fait un cas particulier. Aussi, des zones passive et active ont pu être observées dans les débris indiquant la possibilité d'une rupture progressive vers le bas, rarement observée dans les argiles de l'est du Canada. Les investigations géotechniques de ce cas ont été faites par le Ministère des Transports, de la Mobilité durable et de l'Électrification des transports (MTMDET). Les témoignages donnés lors du procès suivant l'évènement ont également permis de comprendre la séquence des évènements. Cet article présente la description des évènements, ainsi que l'investigation géotechnique complète du glissement.

1 INTRODUCTION

On December 16th 1976, a landslide occurred in the municipality of Saint-Fabien, 270 km east of Quebec City, Canada. This landslide was first studied by the Quebec Ministry of Transportation (MTMDET) during the following year. Particular features of the landslides are its almost horizontal failure surface and the presence of active and passive failure zones in the debris, indicating a possible downward progressive failure mechanism, unusual in Eastern Canadian clays (Locat et al. 2011). L'Université Laval had interest in this unique and well detailed event and decided to study the landslide in detail in 2005, in collaboration with the MTMDET (Levasseur, 2006), and later in 2016 to complete the work.

The purpose of this paper is to characterize and document this unusual event. The landslide itself will be described in the first section. Possible instability triggers and observations of several witnesses will be presented in order to understand its dynamic. Results of the geotechnical investigation will also be presented including geotechnical properties, topography, stratigraphy and hydrogeological conditions of the site. A discussion on the mechanism of the landslide will be given, along with the description of the concept of progressive failure possibly involved in the initiation and propagation of the failure surface. The paper will conclude by describing future works that will be executed to complete the understanding of this event.

2 THE EVENT

The 1976 landslide at Saint-Fabien is delineated by the orange dashed lines on Figure 1 showing a 1977 aerial photograph of the site. It is 600 m wide and 300 m long. Compression fissures can be seen in the debris, north of the road. The landslide took place in a glacial valley filled with glaciomarine clays covered by peat bogs. In the middle of the valley, just north of Road 132, there was continuous exploitation of the peat bog deposit closest to the landslide (see Figure 1). Road 132 and the Canadian National Railway (CN) cross the valley from west to east and were displaced by the landslide movement.

At the time of the event, the MTMDET was working along Road 132. Works started on September 8th 1976 and were supposed to finish before November 8th 1977. Their objectives were to raise the roadway by 0.5 to 1 m and to widen it by approximately 3 m between road chains 252 and 329. The new road was supposed to be located 3 m south of the existing one and the new embankments were not supposed to exceed 1.8 m above the old pavement.

Roadworks between road chains 302 and 310 were finished on November 9th 1976 (Figure 1). Between chains 265 and 297 (Figure 1), roadworks started on October 7th 1976. On December 15th and 16th, the workers were placing the fifth and last layer of embankment fill between those locations. On December 16th, they were progressing from the west toward the east. When the movement suddenly started around 11 am, they were working near chain 289 (Figure 1).

Following the event, the CN decided to sue the MTMDET for the railway damages caused by the landslide that occurred during the roadworks. Records from this lawsuit enabled to obtain several testimonies of the events from eyewitnesses.

Figure 1 : Location of the MTMDET roadworks, the peat bog and witnesses (aerial photograph taken in 1977 after the event, road and CN railway were already reconstructed when it was taken)

The first witness was Mrs. Ginette Gagnon. From the north window of her house (red circle on Figure 1), she had a complete view of the landslide. In her testimony, she assures that she saw the landslide begin at the north-east of the road. At the moment of the landslide, M. Gervais Lepage was operating a truck near road chain 300 (blue circle on Figure 1). At the time of the landslide, he was looking east and said that the first movement started in the north-east area. He located the movement origin precisely in the peat bog. Two other witnesses, M. Camille Gagné and M. Yvon Labris, were also driving trucks and were at chain 310 when they fell in a large crack that opened suddenly (green circle on Figure 1). Both of them climbed on the west edge of the pit and saw that the landslide area was extending. They assure that they saw the movement continue westerly. M. Roger Martin was in his car, in the central area of the landslide, driving west, when the failure occurred (pink circle on Figure 1). He felt his car move and saw ground movement on both sides of the road. When the movement around his car stopped, he got out and ran toward the west and observed that there was still some movement occurring in this area. The location of the truck driver, M. Richard Martineau, is represented by the yellow circle on Figure 1. He was discharging his truck outside and west of the landslide limits. His truck was facing west and he said that he saw the first movement in his rearview mirror. Similarly to M. Roger Martin, he observed movements on both sides of the road. He climbed back in his truck and orientated it toward the east and, at this moment, he observed the subsidence of the road. Finally, the last witness is M. Gilbert Pigeon, a technician at the MTMDET. He was around chain 285, 150 m outside the landslide limits and represented by an orange circle on Figure 1. He mentioned at multiple times during his testimony that the landslide started east and finished west.

In summary, almost all witnesses saw the first movement start in the north-east area, near the peat bog. They saw the landslide propagate toward the west. At the precise time of the event, the MTMDET was working in the western area of the landslide, around road chain 289, at the opposite of the location of the first movement (see Figure 1).

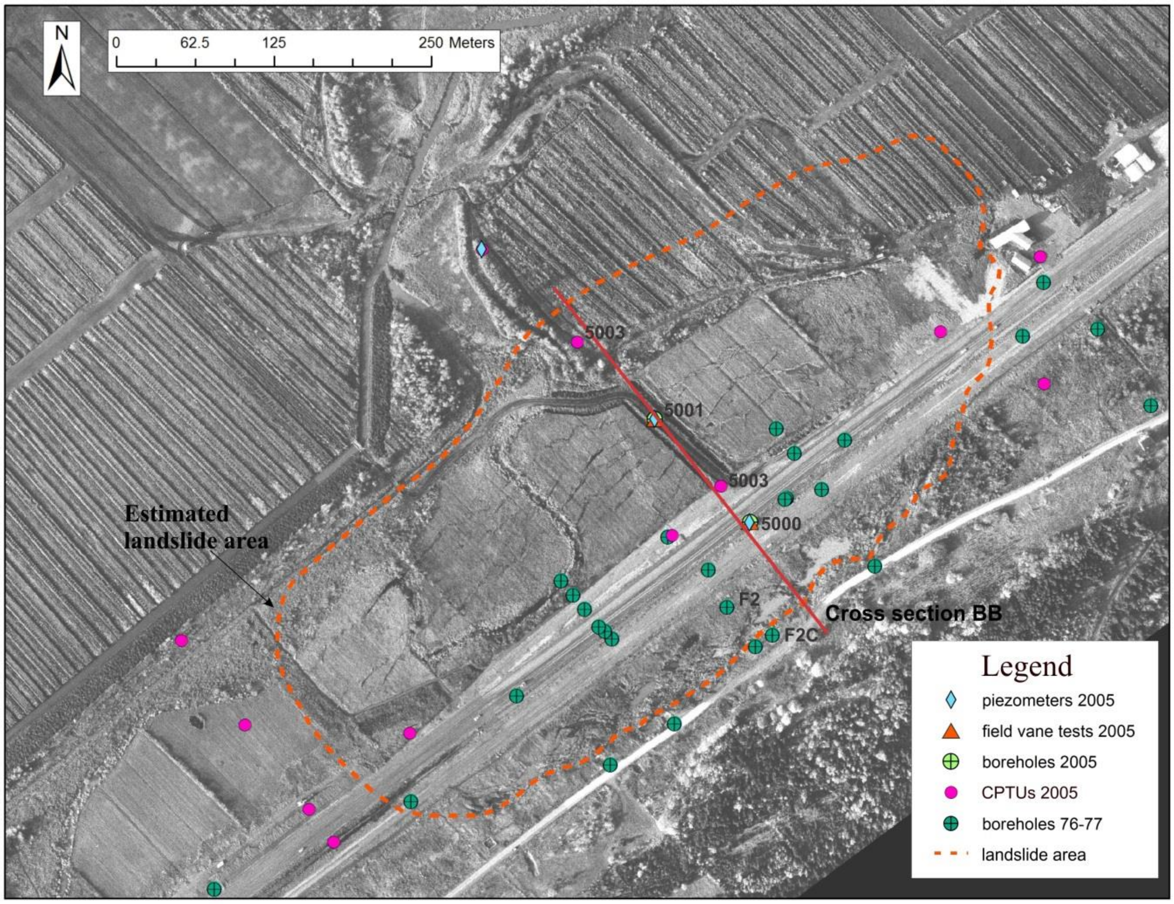

Figure 2: Location of selected boreholes done in 1976 and 1977 and the investigation work done in 2005. Cross section BB is shown in red

3 GEOTECHNICAL INVESTIGATION: SITE AND SOIL CHARACTERISTICS

The geotechnical investigation at the site was performed in two phases. The first phase started in December 1976 and finished in March 1977. The second phase took place between August and October 2005 as part of a research project involving Université Laval. In both cases, the MTMDET was in charge of the investigation. The first phase included 29 boreholes, 26 field vane test profiles and 18 piezometer installations. In the second phase, 2 new boreholes and 2 new field vane test profiles were performed and 3 new piezometers were installed. There were also 14 piezocone penetration tests with pore pressure measurements (CPTUs) that were performed. Selected boreholes done in 1976 and 1977 are located and represented by the dark green dots on Figure 2. Those advanced in 2005 are represented by the light green dots. The field vane tests, CPTUs and piezometers from the 2005 investigation are represented respectively by orange triangles, pink dots and blue diamonds on Figure 2. Laboratory tests were also carried out on samples from locations 5001 and 5000 including grain-size distribution, water content (w), consistency limits (plastic limit, w_p, and liquid limit, w_l) and sensitivity (St) calculated from the intact (Su) and remolded (Su_r) shear strengths from the Swedish fall cone.

A complete geotechnical profile at location 5001, 100 m north of Road 132 in the middle of the landslide area (see Figure 2) is presented on Figure 3. A cross section showing ground surface elevations before and after the event, stratigraphy, water levels from piezometers and the elevation of the failure surface through the landslide area is presented on Figure 4 (see Figure 2 : cross section BB).

3.1 Geotechnical properties at the site

The complete geotechnical profile from location 5001 is presented on figure 3. The upper 3 m consists of peat. This first layer can be easily identified with the CPTU's corrected tip resistance (q_t) of about 300 kPa. The water content in this layer is as high as 743%, which can be typical of peat. The undrained shear strength from vane tests (Su) is about 25 kPa.

The second layer is a soft, sensitive and normally consolidated grey silty clay, with occasional thin layers of sand, presenting variable properties. This layer starts at a depth of 3 m down to a depth of 40 m. The CPTU's corrected tip resistance increases with depth from 100 to 1500 kPa. The water content decreases with depth from approximately 60 % at a depth of 7 m down to 33 % at a depth of 19 m. The liquid limit decreases throughout the layer from 57 % at a depth of 7 m, down to 32 % at a depth of 19 m. The plastic limit is almost constant, varying between 20 and 26 %. The liquidity index therefore varies between values of 1.2 to 3.8 throughout the layer with a surprisingly low value of 0.5 at a depth of 13 m. The soil has a high sensitivity of 57 and 54 at depths of 10 m and 14 m, with lower values of 4 and 9 at depths of 13 m and 19 m, respectively. The plasticity index varies between values of 8 and 31 throughout the layer. The undrained shear strength obtained from the field vane tests (Su) indicates the presence of very soft to soft clay with values from 4 kPa at a depth of 3 m to 18 kPa at a depth of 30 m.

At some locations, the contact between the debris and the intact soil was estimated using CPTUs and field vane tests performed within the landslide limits. This allowed estimating the failure surface at a depth of 10.5 m.

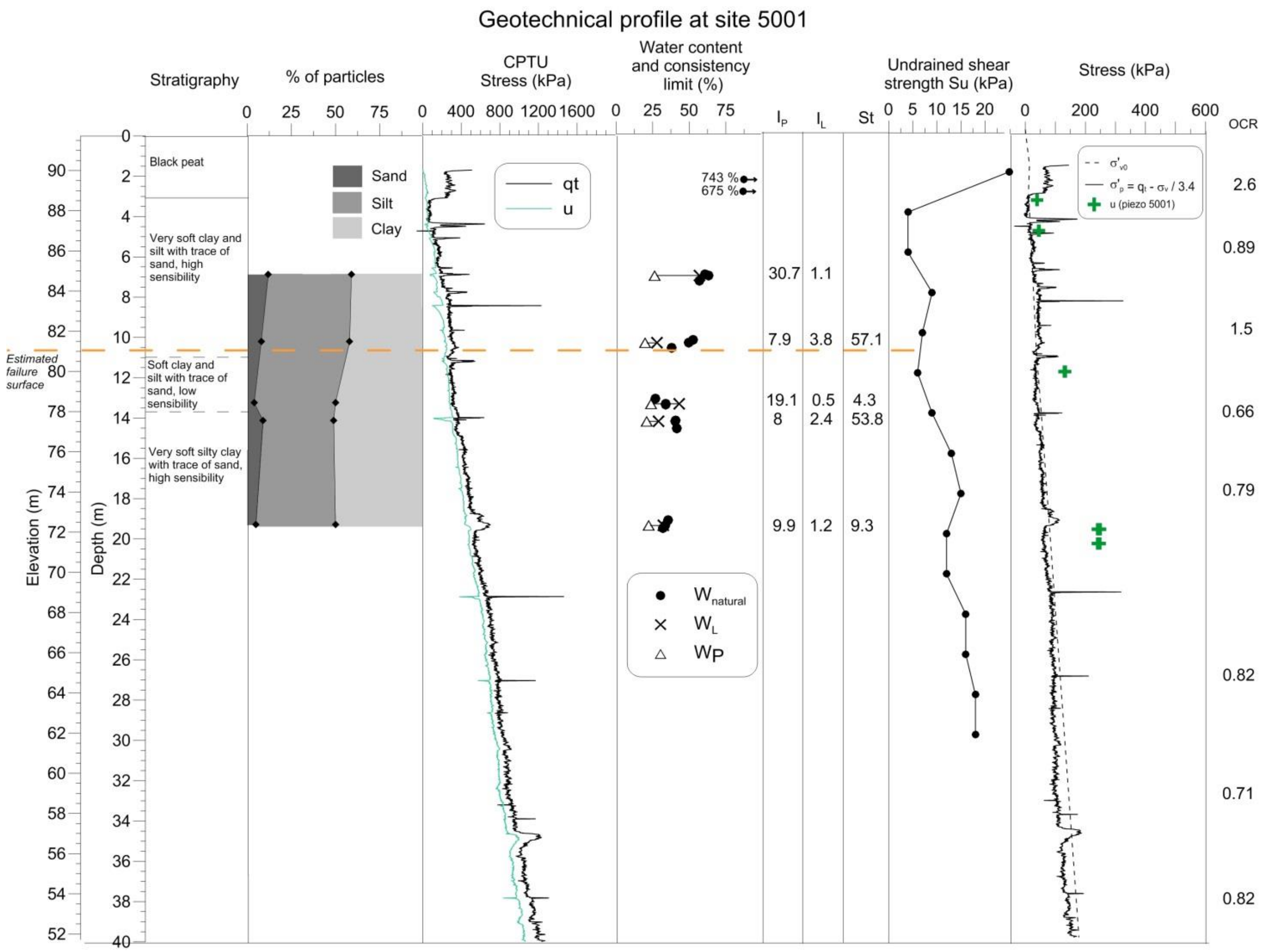

Figure 3: Geotechnical profile at site 5001

3.2 Topography, stratigraphy and hydrogeological conditions in the landslide area

The cross section presented on Figure 4 shows the topography before the landslide, in 1976, and after, in 1977. An active zone of subsidence approximately 2 m deep is visible south of the road, at a distance of 310 m on the horizontal axis of Figure 4. A passive heave zone is located north of the road, with up to 4 m of uprising compared to the initial ground level. This heave zone corresponds to the area where compression ridges can be observed (see Figures 1 and 2). The landslide caused about 20 m of translational movement toward the north. This translation is not visible on Figures 1 and 2 and the cross section (Figure 4), because no aerial photograph was taken before the reconstruction of the road and the CN railway in 1977.

The site stratigraphy was interpreted using information from 4 boreholes (5001, 5000, F-2 and F-2C, shown on Figure 2) and 4 CPTUs (5003, 5001, 5012 and 5000, also shown on Figure 2). The CPTUs were used to determine the depth of the top of the till layer, that was associated with the maximum tip resistance obtained from CPTUs. The stratigraphy of the site consists of a peat layer of 3 to 5 m in thickness and/or a road/rail embankment comprised of sand and gravel of 5 to 7 m in thickness, underlain by a thick layer of soft silty clay, as described in the previous section. The clay deposit is underlain by a till layer of roughly 3 m in thickness resting on bedrock. On Figure 4, it can be noticed that the bedrock surface below the landslide area slopes down in a northerly direction at a relatively constant rate.

The yellow dotted line on Figure 4 shows the elevation of the failure surface as estimated from the CPTUs. The interpreted failure surface elevation is marked with a yellow "x" at locations 5001, 5012 and 5000 at elevations of 81.8, 78.5 and 83 m, respectively. Those are approximatively at a depth of 10.5 m below the initial ground surface.

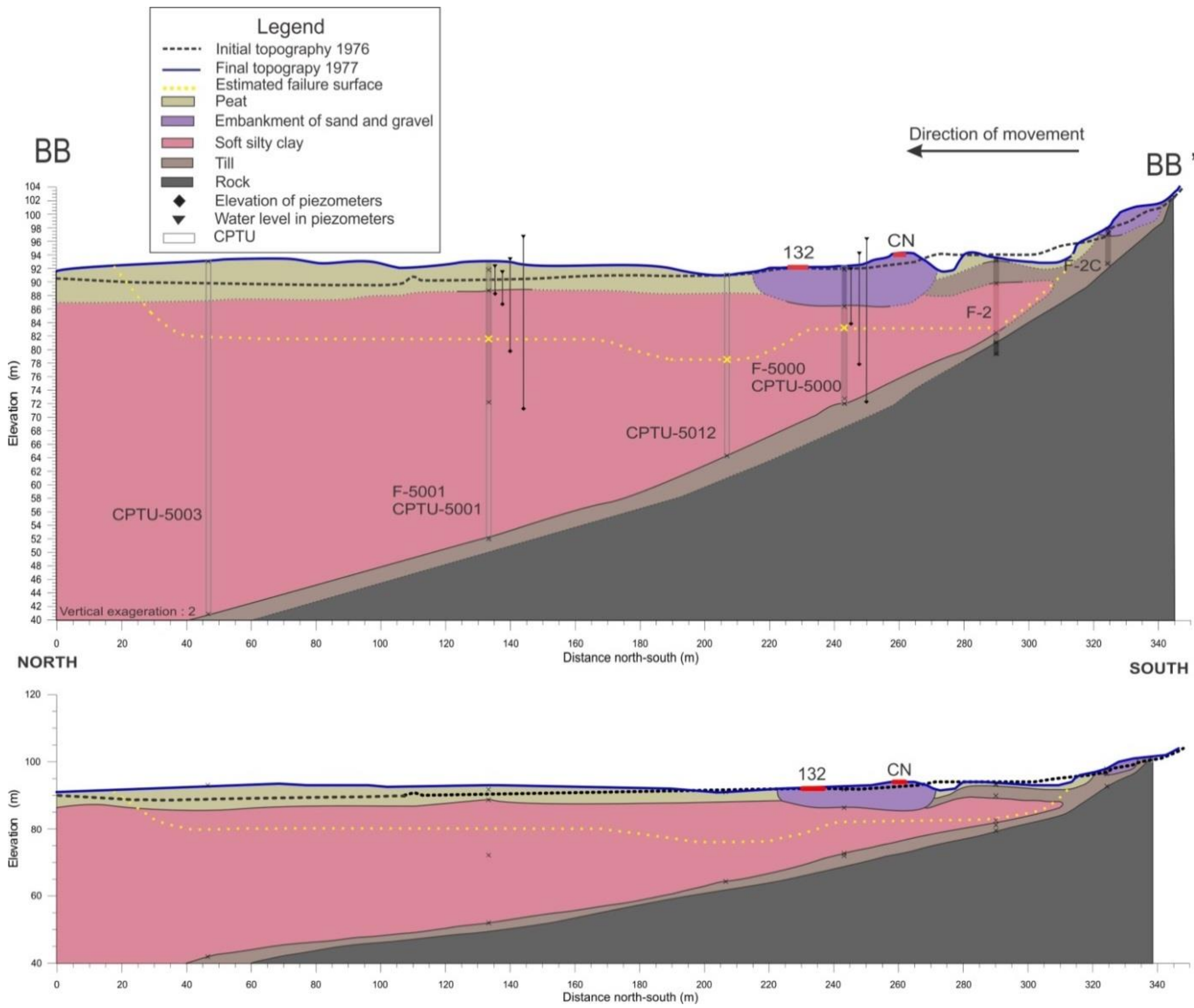

Figure 4: Cross section BB of the landslide showing topography before and after the event, stratigraphy and water level in the piezometers. The upper cross section is depicted with a 2X vertical exaggeration and the lower cross section is depicted with no vertical exaggeration.

The cross section also includes the water levels in piezometers at locations 5000 and 5001. An upward gradient of about 0.30 is noted in the clay deposit at location 5001, and of about 0.39 in the till at location 5000. Those gradients are probably caused by water pressure coming from the outcropping till on the limits of the valley.

4 DISCUSSION ON THE FAILURE MECHANISM

The morphology of the Saint-Fabien landslide described in Section 3.2 shows similarities with downward translational landslides described by Bernander (2000, 2008, 2011) and Locat et al. (2011). Those landslides often take place in slightly inclined slope of normally consolidated sensitive clay. They are generally caused by human activity uphill such as fill loading or pile driving that can increase earth pressures and lead to the formation of a passive failure surface progressing downhill. The typical morphology of those movements consists of an active zone of subsidence uphill and a passive zone of heave downhill. Between those two areas, there is a zone of soil that experiences mostly translational movement.

When a soil deposit presents a strain-softening behaviour during shear, a local disturbance (N_i) applied at the top of the slope can bring the stresses to exceed the peak shear strength (τ_p) locally and decrease toward the large deformation shear strength (τ_{ld}). This may cause a loss of strength at this point that will put additional stress on the clay further downslope. Therefore, this may bring the clay to reach the peak shear strength at this other point, and so on. The main failure then progresses downslope and the large-deformation shear strength (τ_{ld}) and additional pressure will be mobilized along the failure surface (see Figure 5). During this process, if the downslope pressure caused by the progressive failure becomes larger than the passive thrust in the slope, a global passive failure will occur (Bernander 2000, 2008 and 2011, Locat et al. 2011 and Leroueil et al. 2012).

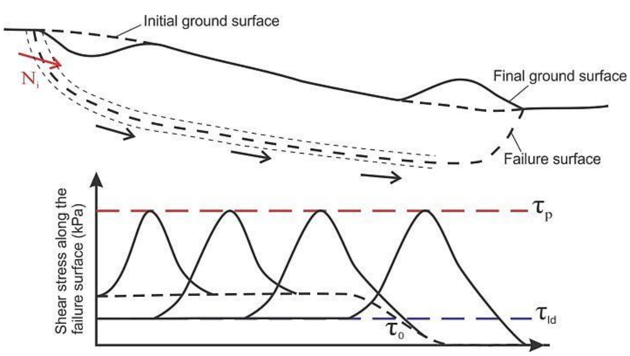

Figure 5: Initiation and propagation of downward progressive failure

Because of the morphological similitudes, the Saint-Fabien landslide will be studied as a downward progressive failure in further works. It will be investigated how the failure surface could have been initiated uphill, causing a downward progressive failure, and how passive thrust could have been reached downhill.

5 CONCLUSION

The Saint-Fabien landslide was investigated at two different times after its occurrence in 1976.The geotechnical properties of the soft silty clay and the morphology was studied in detail as explained in this paper.

At the time of the event, the MTMDET were working west, outside the landslide limit. All witnesses saw the first movement starting from the north-east end of the road and extending south-west. As the morphology of the landslide shows resemblances with downward progressive failure mechanism, presenting an active zone of subsidence and a passive heave zone (Bernander 2000, 2008, 2011 and Locat et al. 2011), the initiation and propagation of the failure will be studied in accordance with this hypothesis.

The next steps of this study are to verify the initiation and propagation of progressive failure with numerical modeling. 1D modeling will be carried out to verify if the concept of progressive failure can explain the initiation and the extent of the observed landslide. The methodology presented by Locat et al. (2013) will be used. It consists of two steps: first to calculate the initial stresses in the slope with the finite element software PLAXIS 2D (PLAXIS, 2015) and second to model the initiation and the propagation of the progressive failure with the finite element code BIFURC (Jostad and Andersen, 2002). 2D modeling is also planned to recreate the morphology of the landslide and to gain an accurate understanding of the event and of the probable downward progressive failure mechanism involved.

6 ACKNOWLEDGMENTS

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