2025 AIGTAS IWLSC

Québec, Canada / 28 septembre au 2 octobre

Issues of highly retrogressive landslides in sensitive clays Champlain Sea Basin

Sainte-Monique, May 15, 2025

Saint-Thuribe, July 21, 2025

Sainte-Geneviève-de-Batiscan

Nicolet, Novembre 12, 1955

3rd International workshop on

Landslides in sensitive clays

Technical tour

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Preface and acknowledgments

This technical tour is part of the 3rd International Workshop on Landslides in Sensitive Clays, an event held in Quebec City from September 28 to October 2, 2025. During the first workshop in 2013, also held in Quebec City, the technical tour focused on various situations along two major rivers in the southern part of the province (the Yamaska and the Richelieu), including cases of rotational landslides and spread (MTQ, 2013).

The 2025 tour includes four stops, located within the boundaries of the ancient Champlain postglacial sea, which help to illustrate various aspects specifically related to the issue of highly retrogressive landslides in sensitive clays, several of which were discussed during the workshop.

The original itinerary has been modified to include visits of two very recent cases of highly retrogressive landslides, which occurred in May and July 2025. These sites will give participants the opportunity to familiarize themselves with this relatively rare type of event.

This guide contains a description of each stop, accompanied by numerous photos, geotechnical profiles, stratigraphic cross-sections, etc. Some aspects are highlighted to encourage discussion among participants during the tour.

In addition to the information provided for each stop, additional information is presented in the form of "capsules" for other sites located along the tour route. These sites, listed in the appendix to this document, will not be visited, but will be pointed out when the bus passes nearby.

The authors would like to thank everyone who participated in gathering information and preparing this document, as well as the presenters for their collaboration during the tour and for their dedication, which was essential to the success of this visit. The authors would also like to thank the authorities of the Quebec Ministry of Transport and Sustainable Mobility, who authorized the preparation of this document and the field visit.

In closing, it should be noted that this version of the document has been slightly modified from the one initially provided to tour participants in order to make minor corrections.

Introduction

In Quebec, the vast majority of the population lives within the boundaries of the ancient Champlain Sea, which occupied the geological region of the St. Lawrence Lowlands between 13,000 and 9,500 years ago (Occhietti, 2007). Beginning around Quebec City and extending westward into the Outaouais region and beyond the borders with the neighboring province of Ontario and the northeastern United States, along the axis of present-day Lake Champlain, the total area of this ancient marine basin is approximately 54,000 km^2 (Figure 1). Clayey soils are found throughout most of this ancient sea but are much thinner on the south side than on the north side of the St. Lawrence River, which lies roughly in the center of the basin. It is around Lake Saint-Pierre, a widening of the river about halfway between the major cities of Quebec City and Montreal, that the thickest clay deposits are found, reaching depths of 80 m or more.

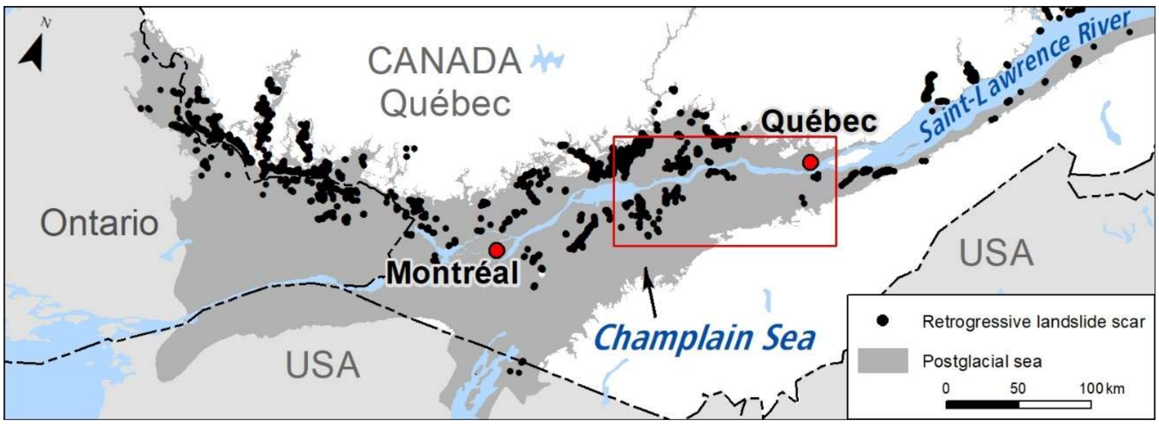


Figure 1 : General location of the Champlain Sea. The red rectangle locates Figure 3 (modified from Demers et al, 2025).

The intense leaching of these marine clays following their post-glacial uplift has led to the development of sensitive clay deposits almost everywhere along watercourses. The highest sensitivity values, some of which can exceed 1000, are more often found on the north shore of the St. Lawrence River, particularly where clay deposits are adjacent to glacial deposits, as in the St. Alban–St. Thuribe area (Paradis et al., 2025), which will be the first stop on the tour.

The recent update of the inventory of highly retrogressive landslides has identified at least 4,420 such scars in the post-glacial seas of Quebec and southeastern Ontario (Demers et al., 2025), including 2,501 in the Champlain Sea basin alone. Research into historical cases (David et al., 2022), which is still ongoing, has so far identified 171 such events between 1770 and the present day, resulting in a total of 151 deaths and at least 58 injuries. In all cases, these events very often cause damage to infrastructure, agricultural and forest land, and always cause significant disruption to the environment, as illustrated by Turmel et al. (2025) and Paradis et al. (2025) during the workshop. Taking 1960 as the starting point, when information began to be better collected, there have been 92 highly retrogressive landslides[1] (HRL) during this 66-year period, 68 of which reached or exceeded an area of one hectare, giving an average of about one case per year.

These clayey soils are prone to various types of landslides, with numerous cases reported to government authorities each year (Poulin-Leboeuf et al., 2022). The most recent compilation of these reports, mentioned by Arel et al. (2025) during the workshop, shows a clear upward trend over the last eight years (Figure 2). From an average of 125 cases reported per year between 2005 and 2016, this value has increased to 268 cases per year since 2017.

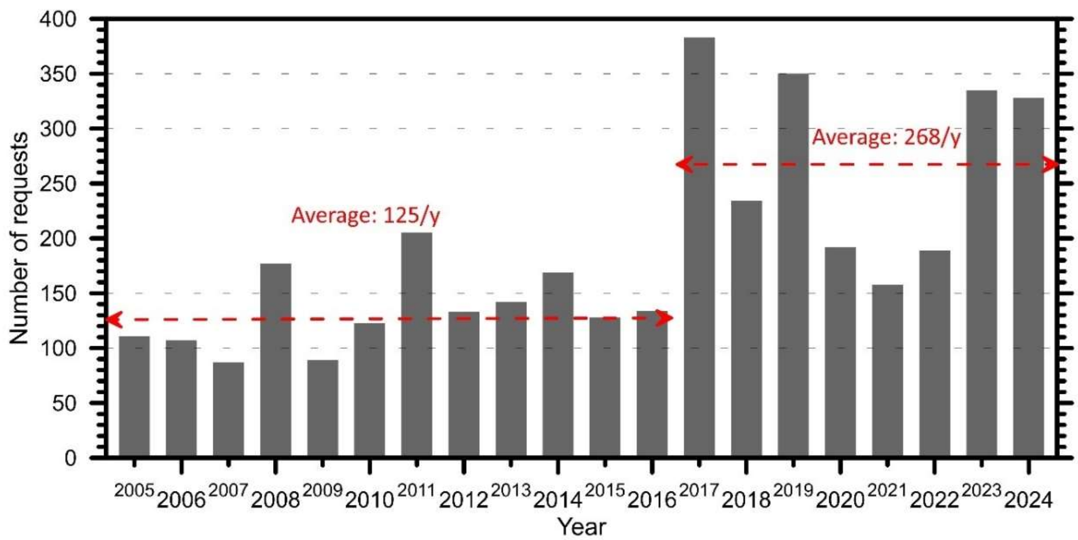


Figure 2 : Number of cases reported to the MSP per year between 2005 and 2024 (taken from Arel et al., 2025)

This recent increase is attributable to two types of extreme weather events. In 2017 and 2019, record amounts of spring rainfall over several weeks, accompanied by snowmelt, were responsible for these exceptional years, during which between 350 and 380 reports were recorded. In 2023 and 2024, it was rather the accumulation of rainfall during violent storms, lasting for short periods (from a few hours to just over a day) and occurring more sporadically, that led to extremely rapid sequences of gully erosion and landslide problems, the vast majority of which were superficial in nature. This type of event puts a lot of pressure on public services to manage these reports in emergency situations.

These extreme weather events, which are often short and intense and cause numerous landslides in clayey soils, are not necessarily linked to the occurrence of highly retrogressive landslides, unless the situation persists for several weeks and is accompanied by more

[1] For its mapping needs related to landslides in clay soils, the MTMD considers landslides to be highly retrogressive if their retrogression distance exceeds twice the height of the slope from which the movement began, or a width exceeding four times that height.

pronounced river flooding, as was the case in the spring of 2017, when three HRLs were recorded during this critical period.

The four sites covered by this tour are located in the eastern part of the former Champlain Sea (Figures 1 and 3). All of these cases mainly concern situations related to the dangers of highly retrogressive landslides. They include two very recent cases (Saint-Thuribe and Sainte-Monique, 2025), as well as an older one (Nicolet, 1955), but also a site where preventive work was just completed in 2024 to protect against this hazard (Sainte-Geneviève-de-Batiscan). Each of these cases is described in the following sections of this document.

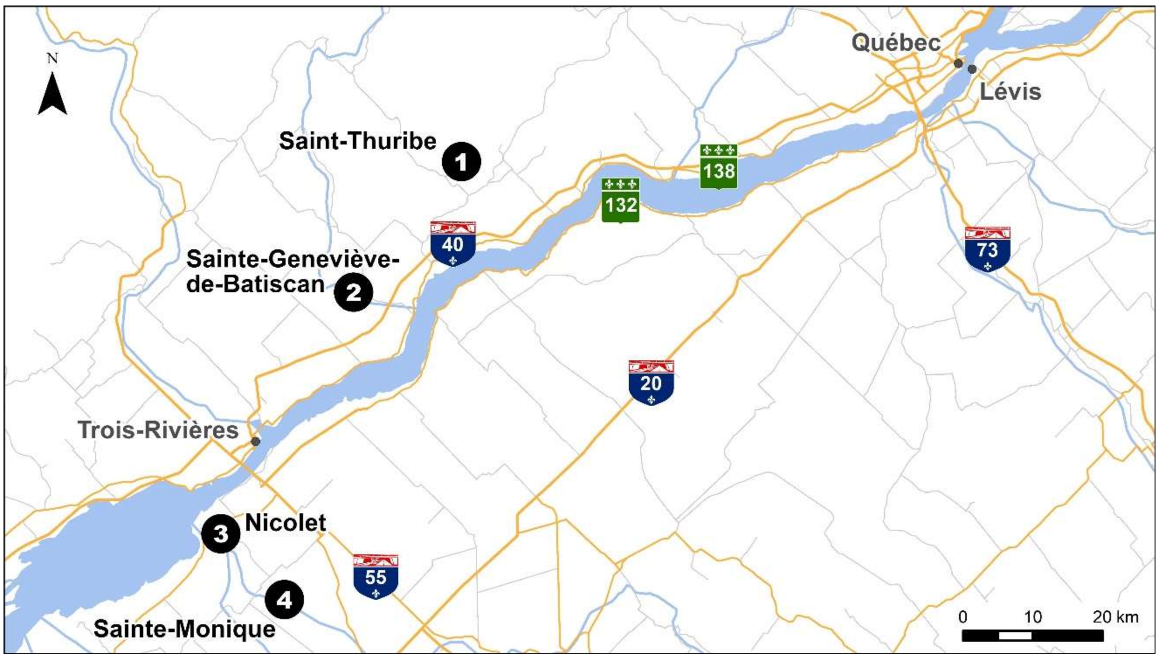


Figure 3 : Location of the four sites visited.

STOP 1 : The landslide of July 15, 2025, Saint-Thuribe

Introduction and historical cases

This first stop in Saint-Thuribe aims primarily to present a case of a highly retrogressive composite landslide, of the flowslide / spread type, which occurred very recently, on July 25, 2025. The site is located in a region that has also experienced several historical landslides (Figure 1), including— a 420-hectare landslide that occurred in 1894 in the neighboring village of Saint-Alban, which was described by Paradis et al. (2025) during the workshop.

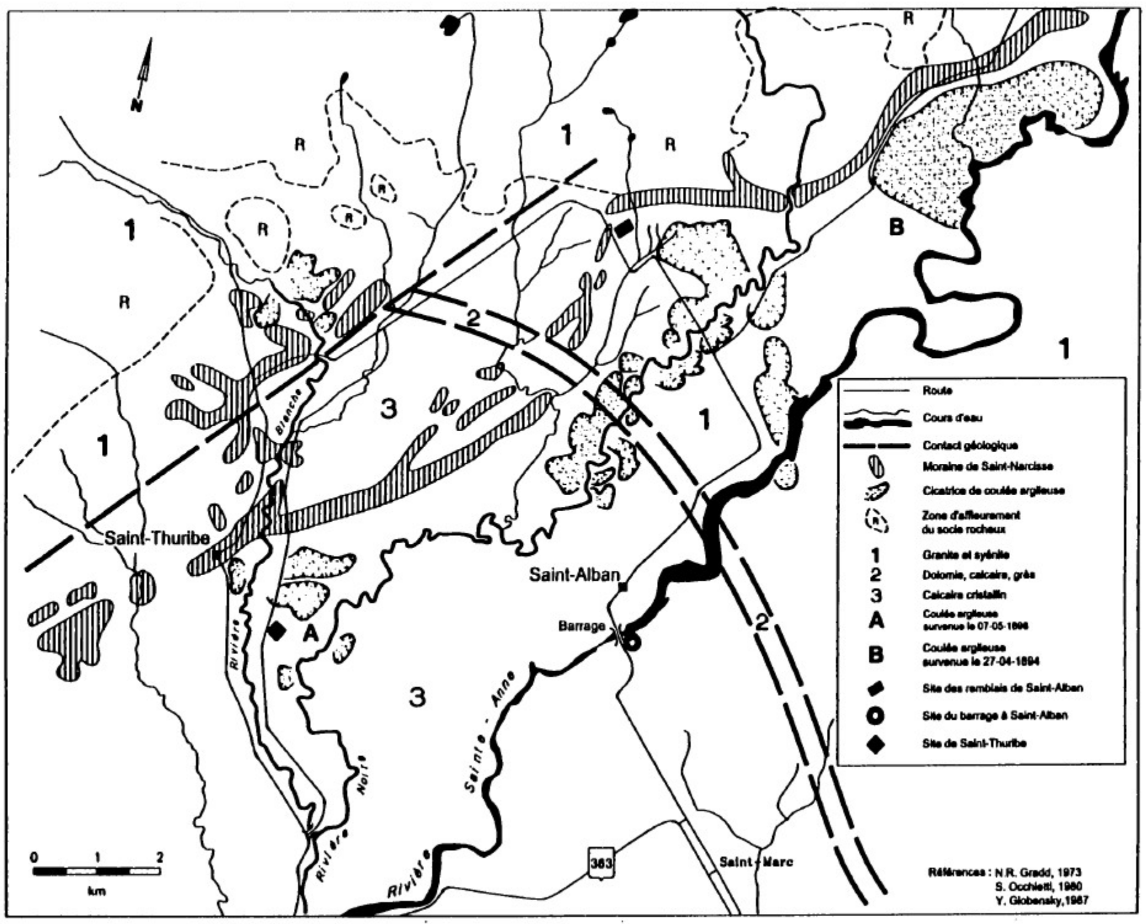


Figure 1: Regional geological context of the St-Thuribe/St-Alban area (from Demers 2001).

The small village of Saint-Thuribe is located in an agricultural region, and its population was 298 according to the 2021 census (Source: Statistics Canada). Although the territory was inhabited as early as the 1830s, it wasn't until 1897 that the parish separated from Saint-Casimir, located approximately 6 km to the south (Source: Commission de toponymie du Québec). Just a year later, a huge retrogressive landslide occurred on May 7, 1898, about 1 km southeast of the village, along the banks of the Blanche River (Dawson, 1899) — the same river along which the July 15, 2025 landslide also occurred.

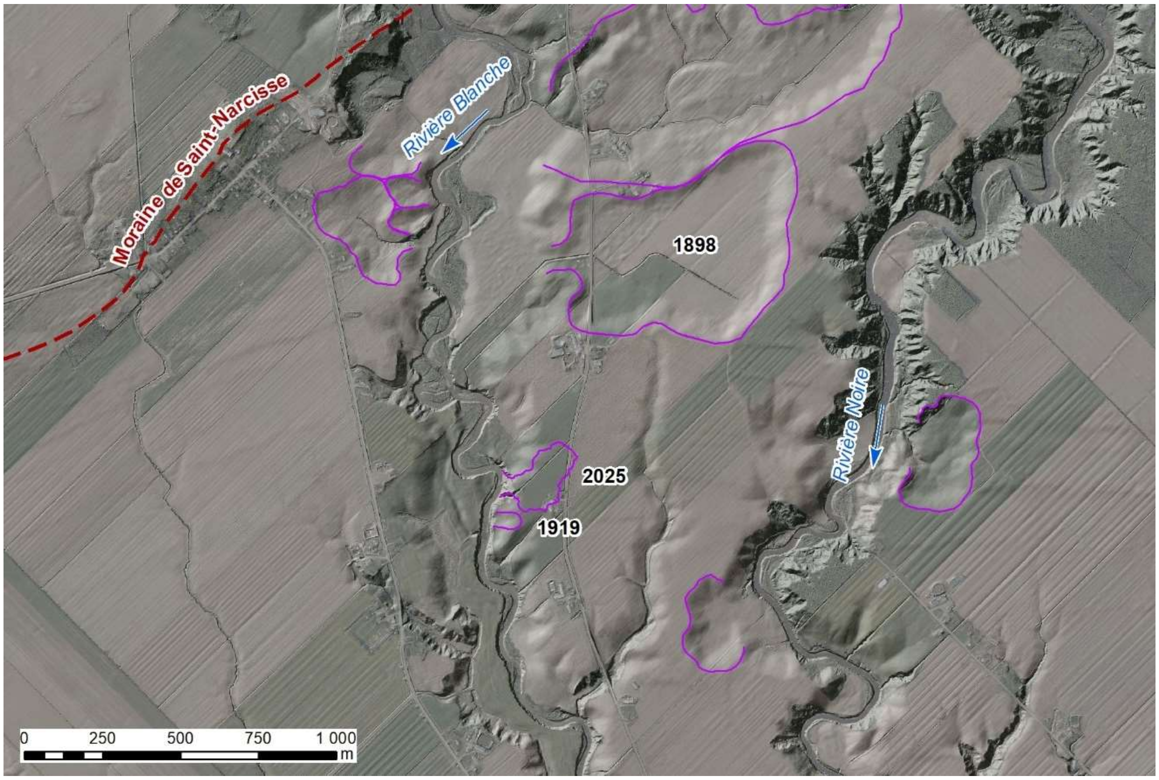


Figure 2: Hillshade image from a LiDAR survey showing the topography of the area and various geomorphological features, including the scars of the highly retrogressive landslides of 1898, 1919, and 2025, as well as the Saint-Narcisse moraine.

The 1898 event occurred at 5:30 a.m., catching residents completely off guard. The Douville family had just enough time to escape their home as the ground collapsed beneath them. Tragically, Régina Douville, about 5 years old, lost her life when her sister, who was carrying her, dropped her during the escape. The overall damage was extensive. Two houses, several farm buildings with animals, a school, a bridge, and a portion of the road were swept away. The losses were estimated at $15,550 at the time.

The movement occurred in several phases. A minor landslide is believed to have occurred the day before the main event, along the bank of the Blanche River, but no alarm was raised as such events were common in the area. However, during the main movement that began the next morning, the first section to break away was estimated at 5 hectares according to newspapers of the time, though it remains unclear how much more followed. The main phase appears to have ended around 11 a.m.. According to eyewitness accounts, the mass of debris moved at the pace of a person walking. Sources indicate that additional sections of land continued to slide over the following two days, and the ground remained too unstable to attempt to recover the victim's body.

Following the landslide, the river was blocked over a distance of 234 meters. The landslide created a 12-meter-high wave that destroyed log booms and formed a jam of timber logs, which amplified the flooding, causing damage to surrounding farmland.

Even at that time, some people began to make the connection between clay and landslides and called for government action: "This entire region is prone to landslides, as shown by the waterways, all muddied with clay, that run through it. Clay is present in large quantities throughout the region, and it is nothing new to point out the frequency of landslides in clayey land. It would therefore be appropriate to ask the government to appoint geologists to study the nature of these soils and to condemn, if necessary, an entire region." (La Presse, May 9, 1898)

This historic landslide, covering an area of 34 hectares, has a characteristic bottleneck shape with a large depletion zone at the back (Figure 2). Based on information provided by Sharpe (1938) (Figure 3), Terzaghi and Peck presented this case in the first edition of their seminal book Soil Mechanics in Engineering Practice, and in subsequent editions (1948, 1967, and 1996). The site is also mentioned by Taylor (1948) in his book Fundamentals of Soil Mechanics. In 1951, Peck et al. conducted one of the first laboratory studies on the behaviour of highly sensitive clay samples collected from this site. The case was long considered a typical example of flowslide in sensitive clay. The sketch made by Sharpe (1938) inspired many subsequent figures in scientific articles on landslides in sensitive clays, depicting a pear-shaped amphitheater and a bottleneck along the riverbank (Chagnon, 1967; Karrow, 1972; Mitchell & Klugman, 1979).

Figure 3: Sketch by Sharpe (1938) of the 1898 landslide in Saint-Thuribe, later used by Terzaghi and Peck in all three editions of their book Soil Mechanics in Engineering Practice.

However, this case was recently re-evaluated by Therrien et al. (2025), who classified it as a composite flowslide-spread type, as several historical photos (Figure 4) and eyewitness accounts from the time clearly indicate the presence of horsts. In his 1899 report, Dawson noted: "The floor of the depression was formed by irregular mounds, pyramids, and blocks of clay [...]". The composite landslide case at Saint-Luc-de-Vincennes in 2016, well documented by Tremblay-Auger (2021), provides a compelling example of a pear-shaped landslide ending in a spread, confirming that this morphology is not exclusive to flowslides in sensitive clays.

Figure 4: Historical photograph showing a horst in the 1898 landslide. View facing the bottleneck part of the slide. (Source: Library and Archives Canada, PA-050914)

The 1898 landslide is not the only one to have occurred in this area, as an even larger scar is visible right next to it, although it happened before the region was colonized. Thus, when a new, smaller landslide occurred on April 4, 1919 (Figure 2), the federal government immediately launched an investigation. Geologists at the time assessed that the retrogression could potentially be as extensive as in 1898 (Wilson & Mackay, 1919). However, no follow-up to this report has been found, making it difficult to determine what mitigation measures were implemented.

Geological Context

The St-Thuribe / St-Alban area is located at the northeastern limit of the Champlain Sea, near the geographical boundary between the St. Lawrence Lowlands and the Canadian Shield, which forms the Laurentian foothills (Figure 1). This mountainous zone lies about 3.5 km northwest of the village of Saint-Thuribe. Another notable geological feature in the area is the presence of a long moraine ridge, known as the "Saint-Narcisse Moraine", which runs roughly parallel to the Laurentian foothills (Figure 1) and marks the position of a glacial readvance within the Champlain Sea, approximately 12,200 to 12,800 years BP (Occhietti, 2007; Parent & Occhietti, 1988).

The July 15, 2025 landslide occurred about 1.6 km south of the Saint-Narcisse Moraine. The presence of the moraine front in contact with the marine basin locally favored the formation of stratified layers within the clay deposits. It also created an upward hydraulic gradient at the base of the clay mass, with intensity varying depending on proximity to the moraine. This environment enabled leaching of the clay deposits, resulting in extremely low remolded strengths—sometimes even below the minimum measurable limit of the Swedish fall cone ($< 0.08 < s_{rc} < 1.19$)—in deeper clay layers. These extremely sensitive layers typically exhibit plasticity index between 4 and 7, liquidity between 2.9 and 5.5 and sensitivity ranging from 120 to 300 (Figure 5). The clay-sized particles (<2 microns) generally average around 35%

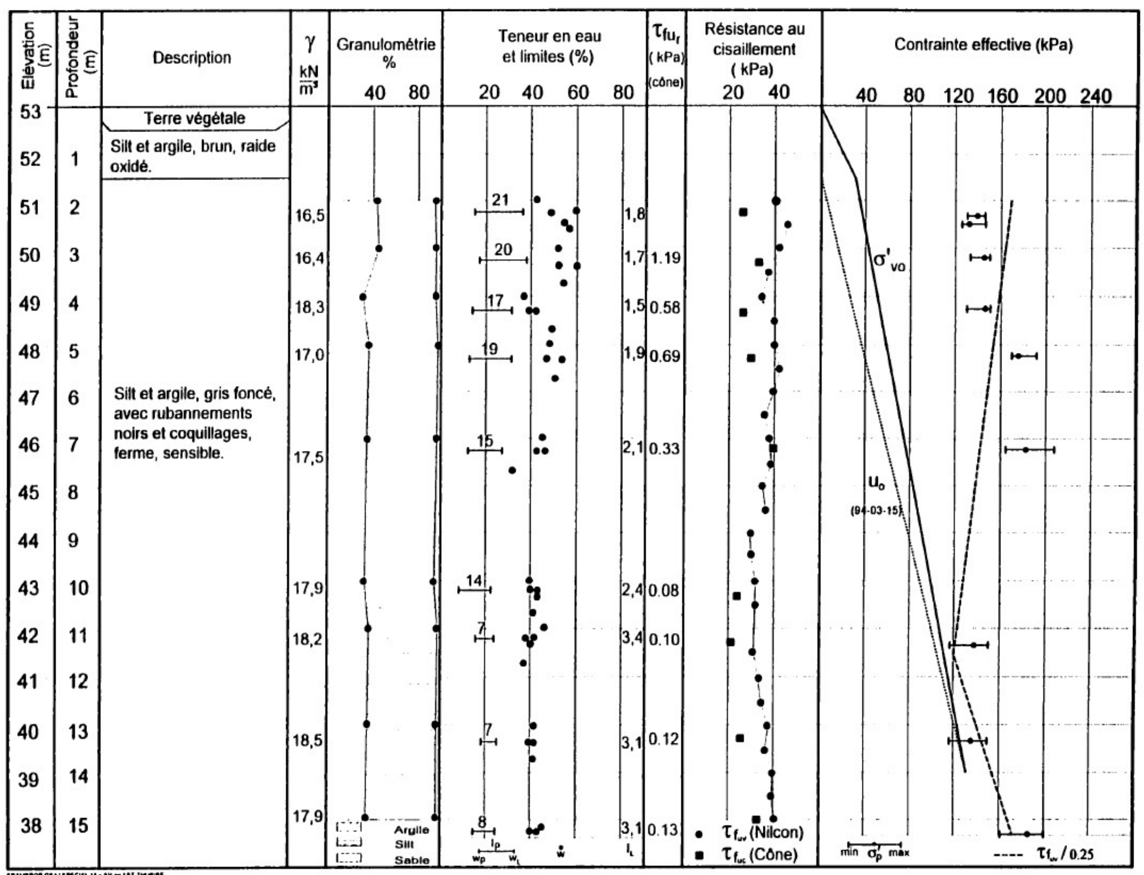


Figure 5 : Geotechnical profile at the site of the landslide of July 15, 2025 (Source : Demers, 2001).

In the landslide zones of 1898 and 2025 at Saint-Thuribe, the clay deposit begins right at the surface and reaches depths of approximately 35 m. Undisturbed shear strength, measured with field vane, ranges from 30 to 40 kPa throughout the riverbank height of the Blanche River, which is about 20 m high.

The Blanche River is a minor watercourse (classified as "Type C" according to Turmel et al., 2025), with a total length of approximately 30 km, flowing primarily through the clay-rich soils of the Champlain Sea basin. Its watershed area covers 217 km^2 (Capsa, 2014). In the Saint-Thuribe area, the river averages about 20 m in width (Figure 2). It forms many meanders, including alluvial plains a few meters high, composed mostly of clay debris from large retrogressive landslides—most notably the 1898 slide and another one just upstream (Figure 2), whose date is unknown, covering about 48 ha. In the outer bends of the meanders, the river sometimes directly undercuts the base of the clay banks, contributing to ongoing instability.

The July 15, 2025 landslide

The landslide of the July 15, 2025, occurred around midnight on the night of July 15 to 16, 2025 (Figure 6). First responders, called in later that night, were deployed to the scene in the early morning hours. The Rivière-Blanche-Est road was quickly closed to traffic, and homes at numbers 20, 25, and 30 were evacuated. Notably, the residents of house no 25 had already voluntarily evacuated shortly before emergency personnel arrived, after observing the formation of a crater near their home. According to the information no precursory rotational landslide was detected along the river in the hours or days leading up to the retrogressive process as is typically the case with this type of event. It is worth noting that a first rotational failure could have occurred unnoticed at the riverbank, especially after dark.

The highly retrogressive landslide exhibited both characteristics of flowslides (strongly remolded and channeled debris carried long distances by the river — see Figure 6) and spreads (presence of horsts and grabens, see Figure 7), as described by Therrien et al. (2025). The large amount of debris that traveled long distances upstream and downstream is typical of a flowslide, while the presence of horsts and grabens among the debris indicates a spreading mechanism. The presence of horsts and grabens both within the scar and downstream of the bottleneck (Figure 6) suggests that flowslide and spread phases likely occurred successively during the event. These features confirm that the landslide kinematics were complex.

Figure 6: Overview of the landslide scar and part of the debris obstructing the Blanche River on July 16. Note the new channel the river has started to follow on the left. (Source: MTMD – DJI_20250718131933_0159)

Figure 7: View of horsts (h) and grabens (g) inside the landslide scar. (Source: MTMD)

The escarpments left by the landslide around the scar were high and steep. According to the digital terrain model (DTM) obtained from a drone photogrammetric survey on July 18, 2025, escarpment heights ranged from 7 to 11 m. Further terrain loss occurred over the following days at the steepest walls, either by rotational failures (Figure 8) or by toppling along subvertical cracks (Figure 9), which were observed in several places within the sensitive clay mass, as described by Lemieux et al. (2025). Two days after the event, the annex behind residence no. 25 was swept away, along with a utility pole. The following morning, the rest of the residence was also carried away (Figure 8). Additional failures were later observed in various parts of the scar's perimeter, including on the municipal road, but these were all limited in size, and debris typically traveled only short distances (Figures 8 and 10). By comparing various digital surface models (DSM) generated from drone imagery in the days and weeks after the event (up to August 18), these additional terrain losses extended no more than 16 m beyond the original edge of the scar as seen on the morning of July 16.

Figure 8: Aerial view of the landslide taken by drone on July 20, 2025. The photo shows the now-destroyed residence no. 25, as well as recent rotational failures (white arrows) around the scar. (Source: MTMD)

Figure 9: Drone photos from July 16, 2025, showing subvertical cracks around the scar, facilitating toppling failures. (Source: MTMD)

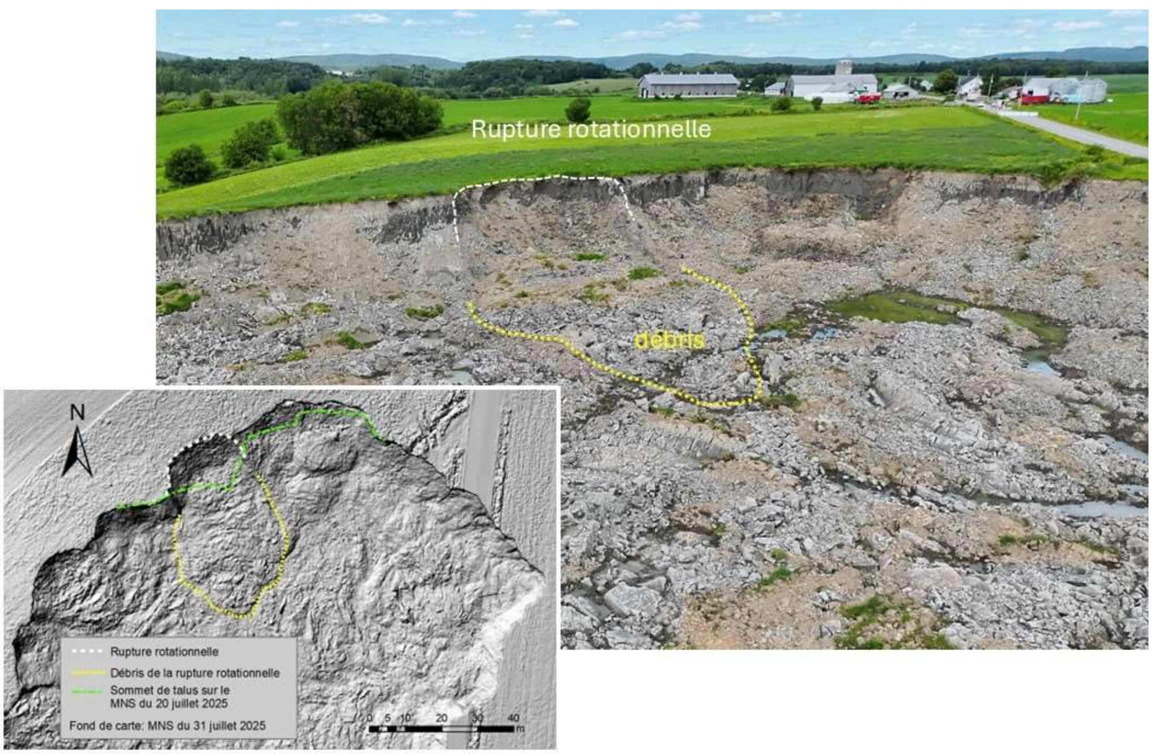


Figure 10: Drone photo taken July 31, 2025, showing an example of terrain adjustment via rotational failure. The inset image shows a top view of the same failure on a DSM derived from photos taken the same day. (Source: MTMD)

According to the most recent survey dated August 18, 2025, the retrogression distance of the landslide is about 230 m, and its width is about 140 m (Figure 11). The total area of soil lost is approximately 30,000 m^2 (3 ha). The municipal road was destroyed over a stretch of about 85 m. On property no. 25, the silo and shed are now only 11 and 12 m, respectively, from the edge of the scar.

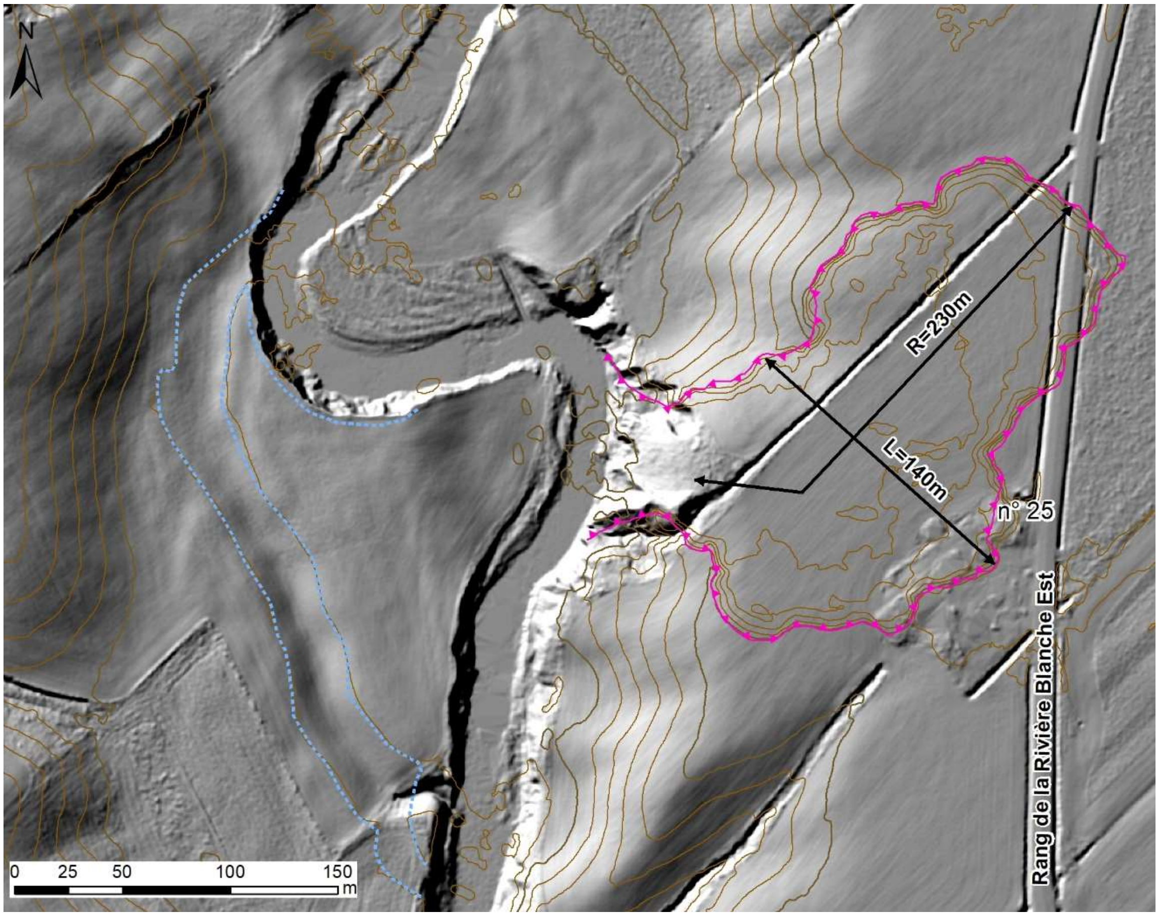


Figure 11: Hillshade image from a 2021 LiDAR survey (pre-landslide), showing 1-meter contour lines (brown) from the DTM of July 20, 2025. It illustrates the scar dimensions and the old channel now being used by the river after the landslide (blue).

The debris from the landslide completely blocked the Blanche River, reaching around 8 m above the water level according to available DTMs. Debris spread along the river for approximately 740 m downstream and 300 m upstream of the landslide. In the hours following the slide, the upstream water level rose by about 6 m, and most of the river's flow quickly rerouted through an old channel located at the foot of the opposite valley slope, whose bed is slightly higher than that of the main channel (Figure 11). Figure 12 shows drone photos of the confluence between the two channels, taken on July 18 and August 12. A satellite image from July 18, 2025 (Figure 13) shows the sediment plume caused by the landslide extending from the Blanche River into the Sainte-Anne River and eventually into the St. Lawrence River, spanning over 46 km downstream of the landslide, reaching as far as

Deschambault and Portneuf. The debris accumulation obstructed the Blanche River for several hours, causing upstream flooding. However, no buildings or infrastructure appear to have been affected by this temporary water retention. On the other hand, the debris significantly altered the river's hydraulic dynamics, including displacement of erosion points and the use of the old river channel on the western valley slope. Due to the large volume of debris, hydraulic disruptions in the Blanche River are expected to persist for several months.

Figure 12: Drone photos at the confluence between the main Blanche River channel and an old branch now carrying the river's flow after the landslide. Arrows indicate flow direction. (Source: MTMD-DGG)

Figure 13: Satellite photo from July 18, 2025 (Source: Sentinel-2 L2A, via Copernicus Browser), showing the sediment plume from the July 16, 2025 landslide. The landslide location is marked by a yellow pin.

STOP 2 - Sainte-Geneviève-de-Batiscan

General information

The second stop on the tour is the municipality of Sainte-Geneviève-de-Batiscan, built at the confluence of the *À Veillet* River and the Batiscan River (Figure 1). The latter is a major tributary of the St. Lawrence River, into which it flows 6 km downstream from the municipality. Its watershed covers 4,690 km^2, along a total length of 192 km, with an average flow of 96 m^3/s (measured 14 km upstream from the village, at the Saint-Narcisse power station). The *À Veillet* River is a minor watercourse with a watershed of 37 km^2. It originates in the Saint-Narcisse moraine area and flows southward for 11.3 km before reaching the Batiscan River.

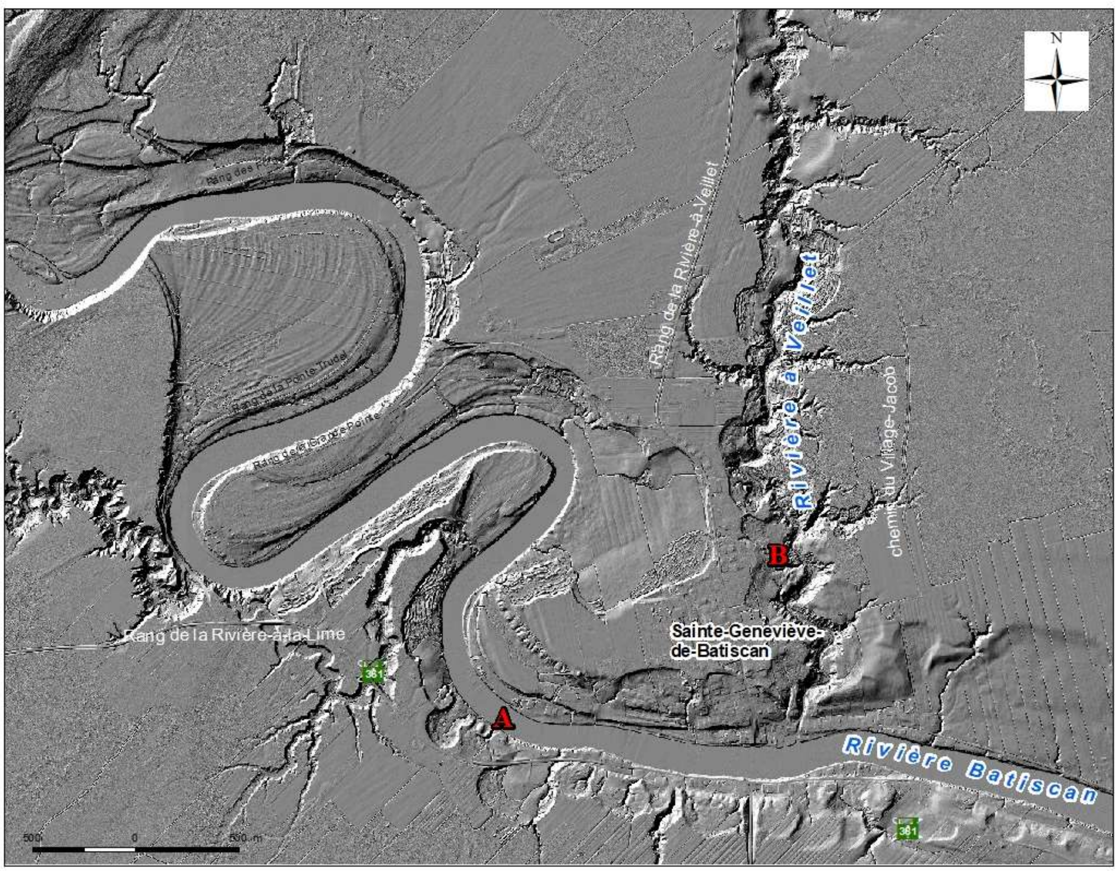
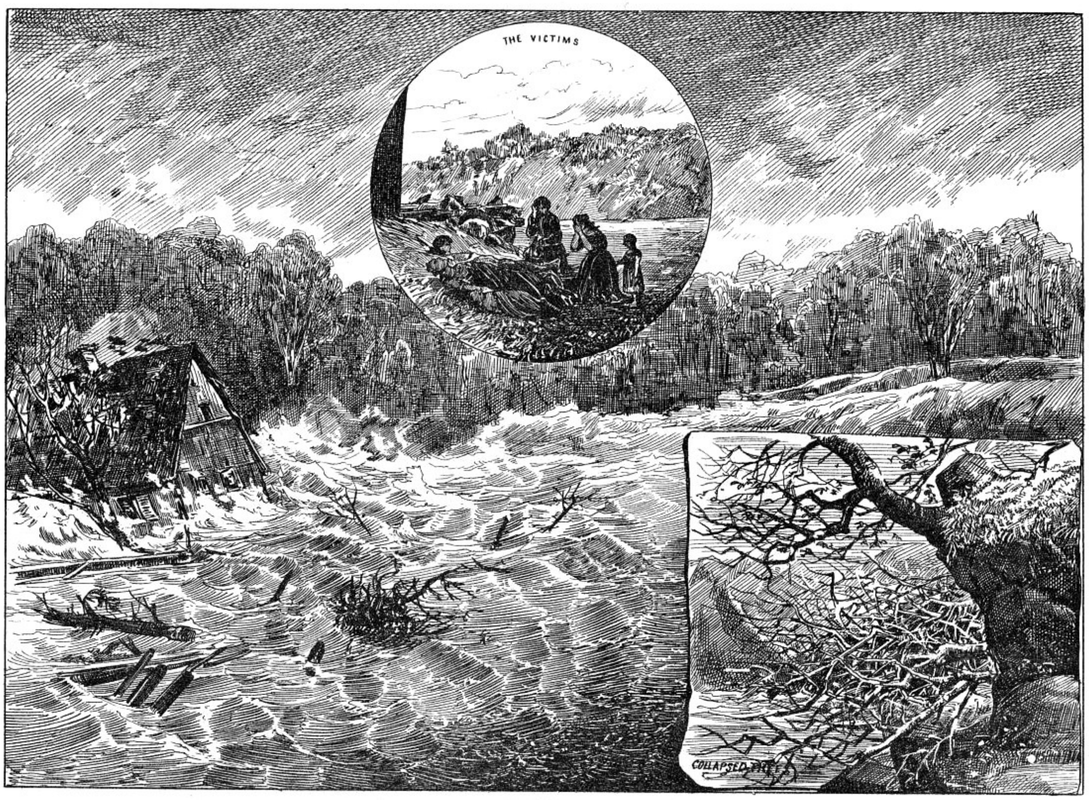


Figure 1 : General location of stop 2 at Sainte-Geneviève-de-Batiscan. A : Rue des Brumes area. B : À Veillet River area.

The downstream course of the Batiscan River and the *À Veillet* River flow mainly through the clayey sediments of the Champlain Sea. Numerous large retrogressive landslides (LRL) are visible on the riverbanks, at least eight of which are historical events (Table 1). Of these eight historical events, none occurred along the Batiscan River; the *À Veillet* River recorded most of them. The oldest recorded case dates back to 1870, along the Champlain River, and resulted in four deaths and three injuries (Lamontagne et al., 2007). The largest of these occurred on May 1, 1877, causing five deaths and four injuries when a 9-meter-high wave caused by the landslide struck a mill further down the river (Figure 2). The other landslides along this watercourse were not as dramatic, but municipal and provincial authorities had to intervene on several occasions to clear the stream and level the affected land (Figure 3). The Marchand Creek was less active, but a landslide on August 9, 1939 (Therrien et al., 2025 a) drew significant press attention because witnesses recorded detailed accounts of the phenomenon. This is how Alphonse Massicotte described what he saw in the August 11, 1939, edition of La Patrie newspaper: "It was as if it [the hill] had melted. Then it began to slide toward the road, blocked for a moment by a concrete culvert. Waves of mud and clay began to pile up to a great height, twice as high as the barn, and soon the culvert was washed away, and everything went into the river 200 feet (61m) below" (Figure 4). The most significant scars are found along the Batiscan River. The largest, located just north of the village of Sainte-Geneviève-de-Batiscan, covers an area of approximately 45 ha (Figure 1).



THE LANDSLIDE AT ST. GENEVIEVE, NEAR THREE RIVERS.

Figure 2 : Depiction of the landslide of May 1, 1877, and its consequences in the newspaper L'Opinion publique *on May 24, 1877.*

Figure 3 : In the 1940s, a program run by the Department of Agriculture allowed farmers to borrow modern equipment to optimize arable land and level of the ground in the landslide site of May 13, 1939 served as a test for this public policy. (Source : Bibliothèque et Archives nationales du Québec, E6, S7, SS1, D2, P381)

Figure 4 : Barely three months after a 6-hectare landslide along the À Veillet *River, another major landslide occurred in Sainte-Geneviève de Batiscan, along Marchand Creek. (Source: Laval University Collections, photo 1653)*

Table 1 : List of historical cases of large retrogressive landslides in the municipality of Sainte-Geneviève-de-Batiscan.

Date	**Watercourse**	**Type**	**Area (ha)**	**Casualties**
1870-10-25	Champlain	Flowslide	4,2	4 fatalities, 3 injured
1877-05-01	À Veillet	Flowslide	8,1	5 fatalities, 4 injured
1902-04-07	À Veillet	Spread	4,5	None
1927-08-16	À Veillet	Spread	1,1	None
1939-05-13	À Veillet	Spread	6,0	None
1939-08-09	Marchand	Composite	5,3	None
1959-11-07	Marchand	Flowslide	0,5	None
2017-04-10	À Veillet	Flowslide	0,7	None

With its numerous historical cases, the municipality of Sainte-Geneviève-de-Batiscan ranks second among Quebec municipalities, tied with Saint-Léon-Le-Grand, for the highest number of recorded cases. In first place, with nine cases, is the neighbouring village of Saint-Luc-de-Vincennes.

Another distinctive feature of the Sainte-Geneviève-de-Batiscan area is the presence of second-generation HRL scars. These are easily recognizable on lidar surveys by the presence of a scar that intersects older ones, with a lower floor, as can be seen in the two examples in Figure 5.

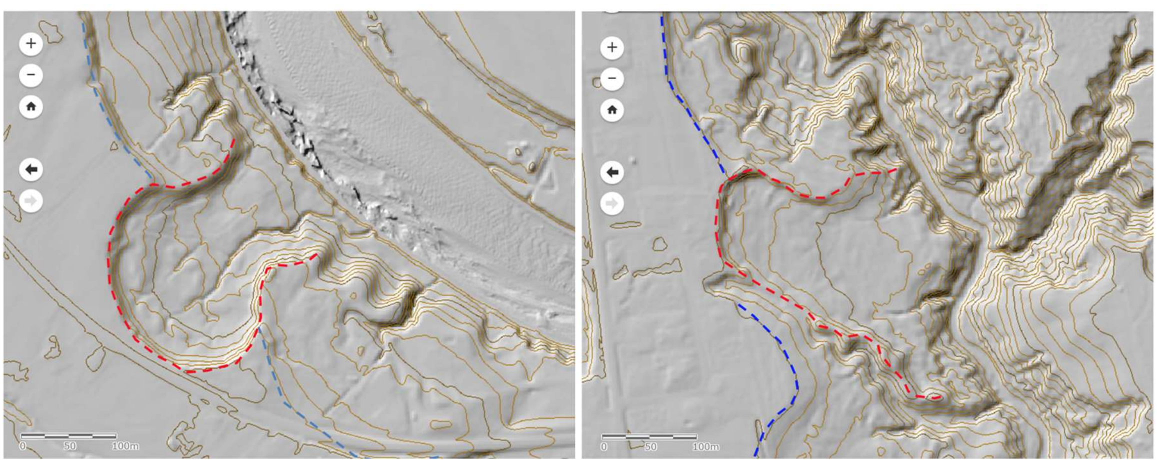


Figure 5 : Examples of first-generation (blue line) and second-generation (red line) scars. Left: Batiscan River. Right: À Veillet *River.*

Stop 2A : Rue des Brumes area – Batiscan River

In November 2016, a rotational landslide was reported on a property located on Rang des Lahaie, in the western part of the municipality of Sainte-Geneviève-de-Batiscan (area not shown in Figure 1). It occurred along the Champlain River, on a slope approximately 22 m high. Cracks extending several tens of meters in length were observed on both sides of the landslide. This site was located approximately 350 m upstream from the historic 1870 event. In addition, several scars from previous highly retrogressive landslides were visible nearby, some of which had retrogression distances of up to 160 m, and one of which covered an area of nearly 10 ha. A borehole carried out at this site in the days following the event confirmed the presence of sensitive clay, with liquidity index ranging from 1.2 to 1.9 at a depth of up to 16 m.

Anticipating the possibility of a major, highly retrogressive landslide potentially starting from this site, it was recommended to evacuate a residence located approximately 145 m from the potential starting zone. The municipality subsequently offered the property owners of alternative plots of land for safe relocation, based on the landslide hazard maps of the sector produced by the Ministry of Natural Resources (MRN) in the 1980s. Concerned about avoiding experiencing similar problems in the future, the owners nevertheless inquired sought confirmation from the Department of Public Safety (MSP) about the safety of their preferred sites. The MTMD was then mandated to analyze the situation in detail.

One of the lots submitted for review was located on Rue des Brumes, situated on an alluvial plain a few meters above the average level of Batiscan River. This site was not identified on the 1980's map as exposed to retrogressive landslide hazard. However, the mapping at that time did not delineate the areas that could be hit and buried by debris from a major landslide, even though this was a real possibility for the site on Rue des Brumes. A potential trigger zone for this type of hazard had been identified on maps from the 1980s, right across the river (Figure 6). A detailed geotechnical study was therefore undertaken, first to verify the soil properties at the starting point on the opposite bank, and secondly to assess whether debris from a HRL that would occur there could be damaging to the Rue des Brumes area, where a few permanent residences had already been built (Figure 6).

Results of soundings and drilling carried out on the opposite bank confirmed that the clayey soils forming the slope were indeed prone to the development of HRLs, which was to be expected given the numerous scars left by such movements in the area (Figure 6). According to borehole 26026, located at the top of the slope, liquidity index varies between 1.3 and 1.6 throughout the clay column forming the bank (Figure 7). And although the potential starting point was located within an old first-generation scar, the part of the slope directly adjacent to the river, consisting of intact clay, remained approximately 14 m high, and at a "critical" slope, considering the properties of the clay. In addition, the foot of the slope showed signs of active erosion (Figure 8).

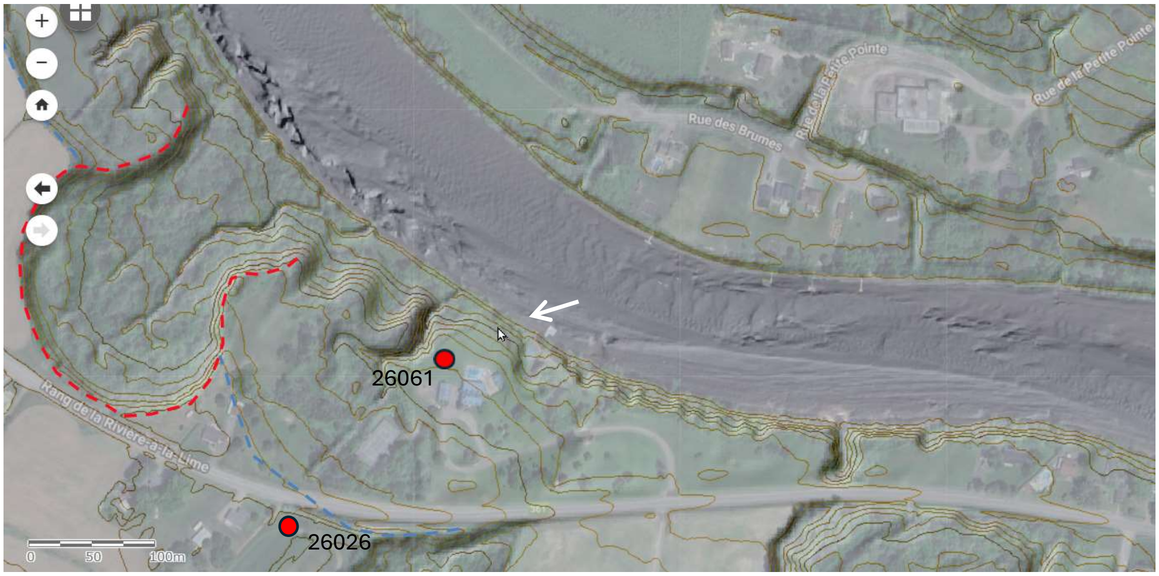


Figure 6 : Location of the Rue des Brumes area and the potential starting point on the opposite bank of the Batiscan River, indicated by the white arrow. The bathymetry shows a deeper underwater channel in the outer curve of the meander. The red dots indicate the locations of the soundings carried out for the study. Isocontours are spaced at 2m intervals.

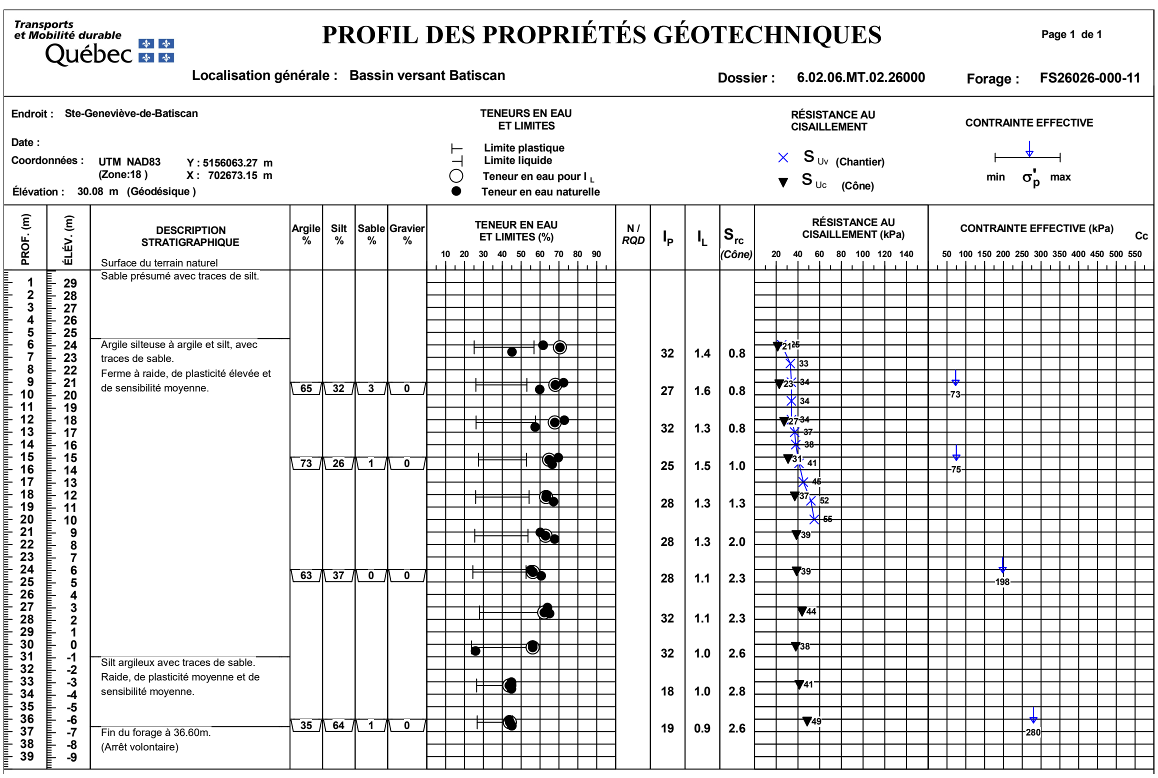


Figure 7 : Geotechnical profile of borehole 26026, located at the top of the slope on the opposite bank from Rue des Brumes (location shown in Figure 6).

Figure 8 : Helicopter view of the riverbank opposite Rue des Brumes, showing signs of active erosion at its base.

Regarding the issue of debris propagation, two analyses were conducted to assess the danger for the alluvial plain of Rue des Brumes, opposite the starting point. At this location, the two banks are approximately 110 m apart. According to the empirical approach presented by Turmel et al. (2018), the situation did indeed seem worrying, since the bank near Rue des Brumes was slightly lower than the average thickness of debris compiled for historical flowslides (0.2Htotal – Demers et al. 2014). Consequently, a numerical simulation was undertaken to refine the diagnosis, following the model and approach presented by Turmel et al. (2017a, 2017b), which also considers the danger of tsunamis caused by debris entering the watercourse. Locat J. et al. (2016, 2017) reported cases of tsunamis associated with highly retrogressive landslides in Quebec, including the deadly 1908 Notre-Dame-de-la-Salette disaster, which occurred in a context similar to that of the Rue des Brumes site.

Figures 9 and 10 illustrate some of the results of this numerical analysis (Turmel and Locat, A. 2020), which confirmed that the Rue des Brumes area was indeed potentially at risk. Both 2D and 3D numerical analyses were performed using two different software programs. The 2D analysis considered the potential retrogression speed of landslide, and the 3D analysis accounted for presence of water in the river, allowing simulation of the impulse wave (tsunami) created by the debris mass entering the channel. Two volume scenarios were studied, with varying material and accounting for the energy required to remould the clay, in order to determine the possible extent of the debris and the wave. Both 2D and 3D results showed that for most simulations of a smaller landslide scenario, the debris will either accumulate on the opposite bank, blocking the river, or spread across the alluvial plain on the opposite bank. The modeled travel distances are not identical in 2D and 3D, which could be due, among other things, to the impact of water on debris propagation in 3D cases (Figure 10). The same conclusions also apply in the case of a larger landslide scenario, characterized by greater volume and higher average energy. In this case, with average parameters, the debris would cover the opposite bank, and the wave produced would also reach the terrace located at a higher elevation.

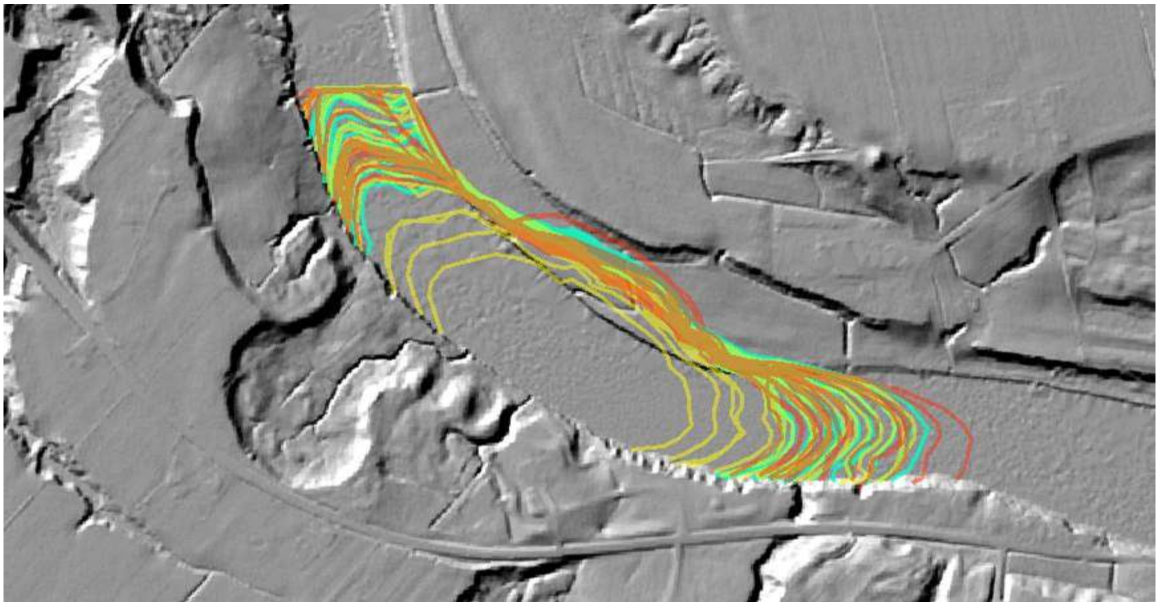


Figure 9 : Results of all 2D modeling performed for the smaller of the two scenarios (comparable to that of the second generation HRL just to the northwest). The lines of different colours illustrate the distances that debris could reach by varying the value of the yield strength, the energy required to remould the material, and the speed of retrogression.

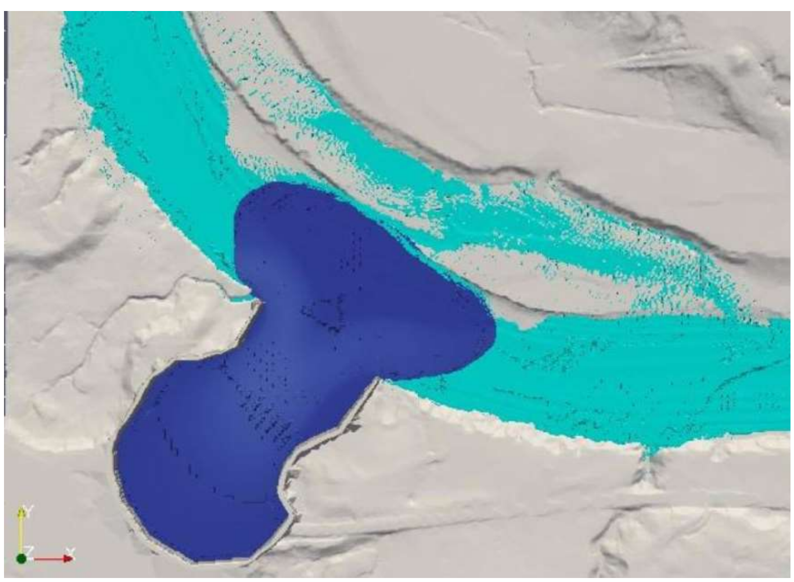


Figure 10 : Results for a yield strength of 750 Pa and an F_{ER} of 0.1 for the 3D modeling of the smaller landslide scenario. The simulation shows that water, represented in light blue, could reach and flood most of the alluvial plain of Rue des Brumes when pushed by debris from the landslide.

Although the concerned owner affected by the November 2016 landslide ultimately did not choose the Rue des Brumes site for relocation, the problem remained for the residences already built in this neighborhood. Various mitigation measures were considered, including the construction of a barrier along the edge of the floodplain to divert any debris from landslides or tsunamis. Such a structure would have cut off residents' access to the river.

The chosen solution was to stabilize the potentially unstable slope on the opposite bank, since it was the only one that could threaten the Rue des Brumes area and the stabilization required only minor work, with approximately 60 m of riverbank to protect (Figure 6). The work therefore consisted of installing riprap at the foot of the problematic slope, serving both as a counterweight and protection against erosion (Figure 11). Figure 12 shows the results of the stability calculations for the chosen solution.

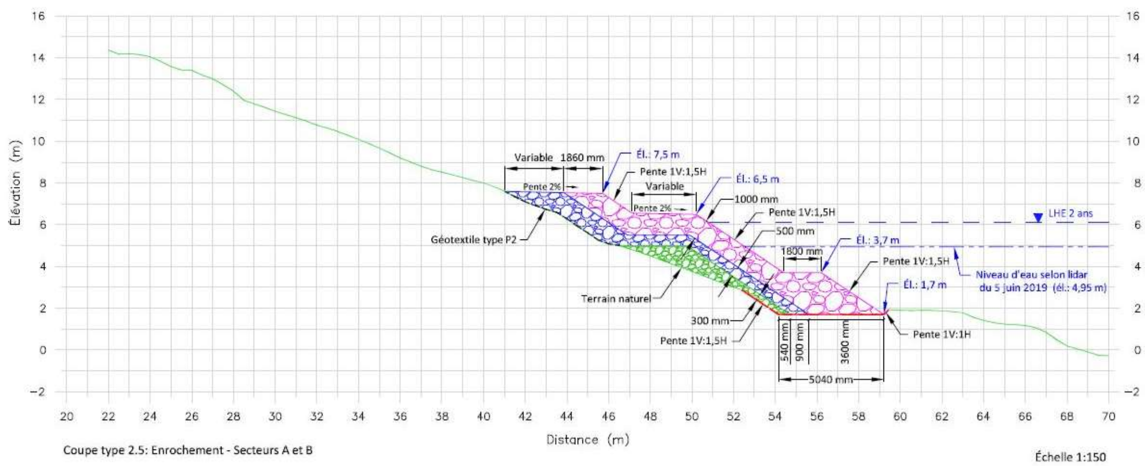


Figure 11 : Typical cross-section of riprap along the Batiscan River. Note: the figure shows only the lower half of the slope.

Though not complex from a geotechnical standpoint, implementation of the rockfill solution nevertheless was constrained by environmental considerations. Special precautions and measures had to be put in place to account for the site's hydraulic and wildlife characteristics in order to obtain environmental permits. On the one hand, the site was identified as a habitat for several species, including a freshwater mussel that is endangered or threatened under the Species at Risk Act. For this reason, Fisheries and Oceans Canada required that an inventory and relocation be carried out by a specialist during the summer preceding the stabilization work.

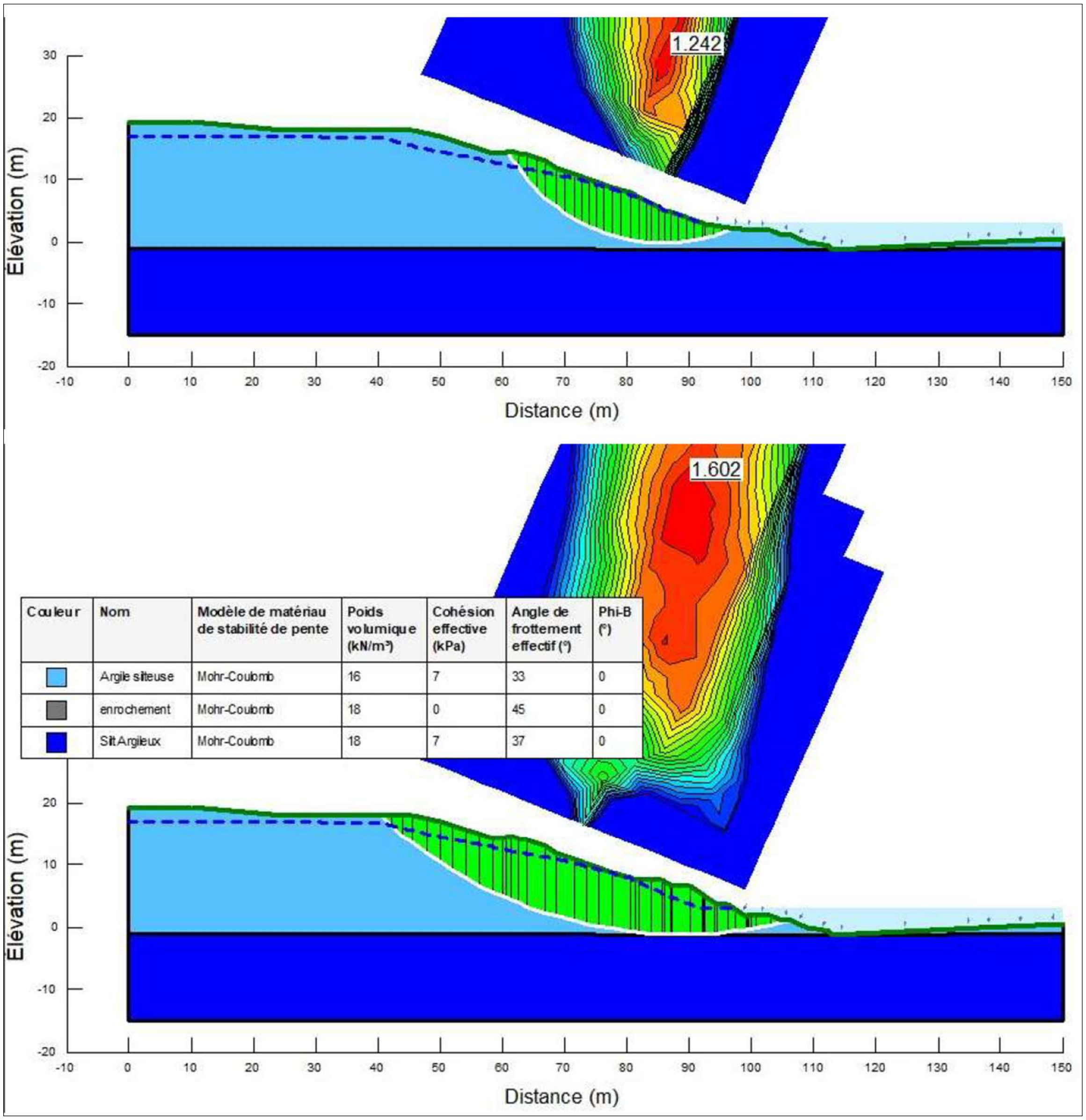


Figure 12 : Stability calculation for the natural slope (top image) and for the slope with riprap at the base (bottom image).

On the other hand, an ice jam problem known to occur in this section of the Batiscan River required a significant redesign to modify the geometry of the stabilizing counterweight and minimize its encroachment into the river. The value measured at the elevation of the 2-year recurrence high water line (HWL), was critical, as this value is taken into account in assessing the riprap's impact on ice jam formation. Figure 13 shows the work in progress during its final phase and after completion.

Figure 13 : *Stabilization work opposite Rue des Brumes, on the Batiscan River. Left: work in progress. Right: 11 months after completion of the work.*

Upon completion of this stabilization project the area potentially exposed to landslides, which had been identified in the 1980s, was removed from the landslide hazard map, protecting not only the residents of Rue des Brumes, but a few more homes and a a segment of the road on the opposite bank, which were at risk of being swept away by a second generation of HRL. This also freed up some potentially buildable land, which was another advantage for the municipality.

Stop 2B : Preventive works – *À Veillet River area*

Among the relocation sites proposed by the municipality of Sainte-Geneviève-de-Batiscan following the 2016 landslide along Rang des Lahaie, there was another site located closer to the heart of the village, near a stream called *À Veillet* River (Figure 14A). The 1980s mapping did not identify any areas potentially exposed to highly retrogressive landslides at this location, even though the slopes are approximately 18 m high. The proposed site was in fact located within an old scar left by a HRL that had occurred on a bank with an initial total height of 26 m. The presence of this scar may explain why those responsible for mapping at the time did not map any area beyond a protection strip equal to twice the height of the current slope.

However, recent lidar data has revealed the presence of ancient, second-generation HRL in the area (see image on the right in Figure 5). In addition, a recent piezocone survey conducted within the old first-generation scar at the site detected its slip surface at a depth of approximately 8.7 m, or about 11.3 m above the current water level of the *À Veillet* River (Figure 14B). According to samples taken from the borehole adjacent to the piezocone, the debris above the slip surface (first 8.7m) has liquidity index ranging from 1.3 to 2.0, while the underlying intact clay, located above the river level, has liquidity index between 1.1 and 1.2 and sensitivity values between 26 and 30. Although this intact clay unit does not have the necessary characteristics for the development of a flowslide, these values could nevertheless be sufficient for a spread to develop (Leroueil et al., 2025; Therrien et al., 2025). In addition, recent observations have shown that the foot of the slopes in this area is affected by active and sometimes very severe erosion by the river (Figure 15), which is contributing to a gradual decrease in the overall stability of the slope.

This preliminary analysis led both, to a decision to recommend the municipality not to propose this site and to a review of the mapping of the area, given the presence of numerous nearby buildings. Data from two other boreholes drilled within the village boundaries (26026 and 26040) showed that the clay was even more sensitive there, with liquidity index between 1.3 and 1.8, and remoulded shear strengths varying between 0.2 and 0.8 kPa in the upper two-thirds of the clay deposit, making it prone to flowslides.

These more detailed geotechnical data of the area, combined with field observations of the active erosion of the river , as well as the historical context of the watercourse, where five HRL events have occurred since 1870, led to the conclusion that preventive bank stabilization work in the village area was relevant.

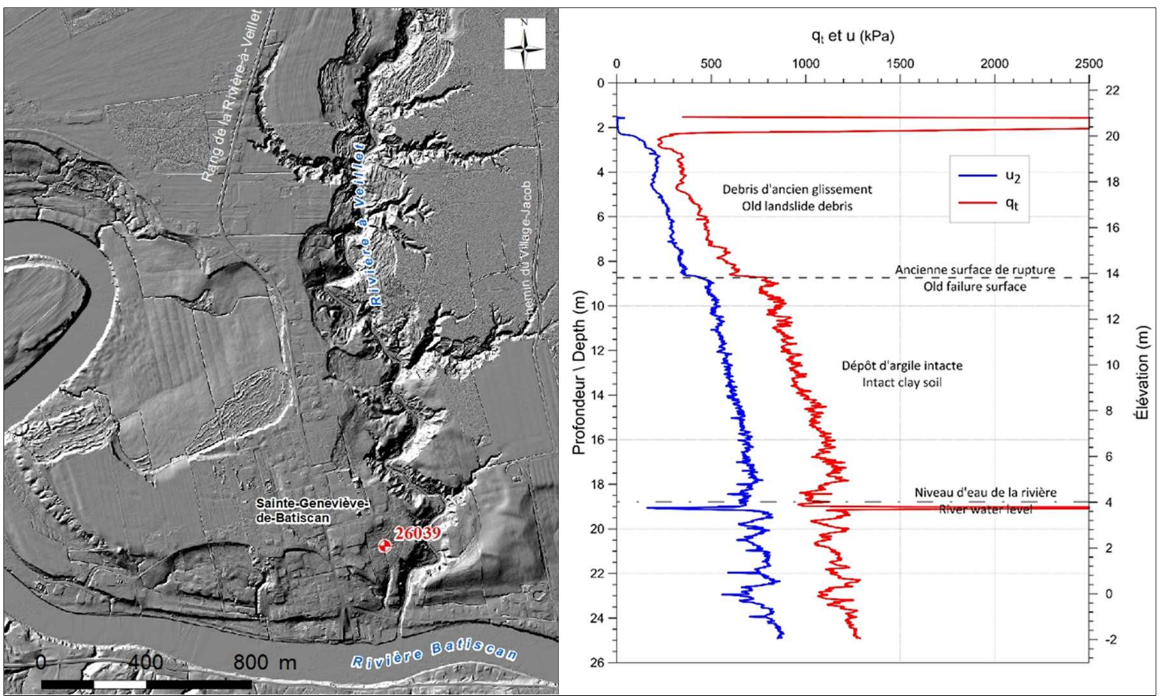


Figure 14 : A (to the left) - Location of the À Veillet *River area and position of borehole 26039 in red. B (at the right): Piezocone sounding profile 26039.*

Figure 15 : View of erosion at the foot of the slopes along the Veillet River near the village of Sainte-Geneviève-de-Batiscan. Total height of the slope: 26 m. (Source: MTMD – 2017).

However, the *À Veillet* River poses significant challenges for stabilization work due to its ravine-like configuration: very steep slopes, narrow watercourse, sporadic alluvial plain, pronounced longitudinal slope of the thalweg, and active erosion along its entire length.

In addition, with a view to improving practices and minimizing environmental impact, the *À Veillet* River site was chosen as a pilot project with the aim of becoming a reference for future stabilization projects. To this end, an initial characterization to measure various aspects of the watercourse (water quality indices, hydraulic monitoring of drought conditions, etc.) is planned just before construction begins. Monitoring will then be implemented in the following years to identify and quantify the longer-term impacts of the project on the environment. The characterization and long-term monitoring are carried out by a multidisciplinary committee composed of various departments within the MTMD specializing in distinct areas of expertise: Geotechnical and Geology (DGG), Hydraulics (DH), and Environment (DEnv).

In addition, to facilitate the acquisition of the requires environmental permits the work is being designed in consultation with the various members of the multidisciplinary team: the DGG is responsible for geotechnical design, the DH for hydraulic design, and the DEnv for including proposals for self-compensating environmental measures. The aim of this multidisciplinary approach is to integrate, from the outset, several elements that will contribute to enhancing the environmental value of the project.

For the moment, the design is at an embryonic stage. A stabilization concept combining geotechnical and hydraulic aspects has been selected to cover 1,750 m along the main watercourse over. This does not include the transitions upstream and downstream of the area to stabilize, nor the riprap at the small tributaries of the *À Veillet* River.

In short, the chosen concept is typical of this geomorphological context (Demers et al., 2025) and consists of raising the riverbed by 1.5 m and installing a counterweight on the banks where stability has been deemed precarious. The concept varies along the course depending on the presence of sporadic floodplains. Where a floodplain is present, the counterweight is applied to a single bank and the floodplain is protected against erosion by embedded riprap (section type 1, Figure 16). Elsewhere, where both banks are unstable slopes or where the stream geometry is too narrow, riprap counterweights are required on both sides of the stream (cross-section type 2, Figure 16). Figures 17 to 20 show the results of the stability calculations.

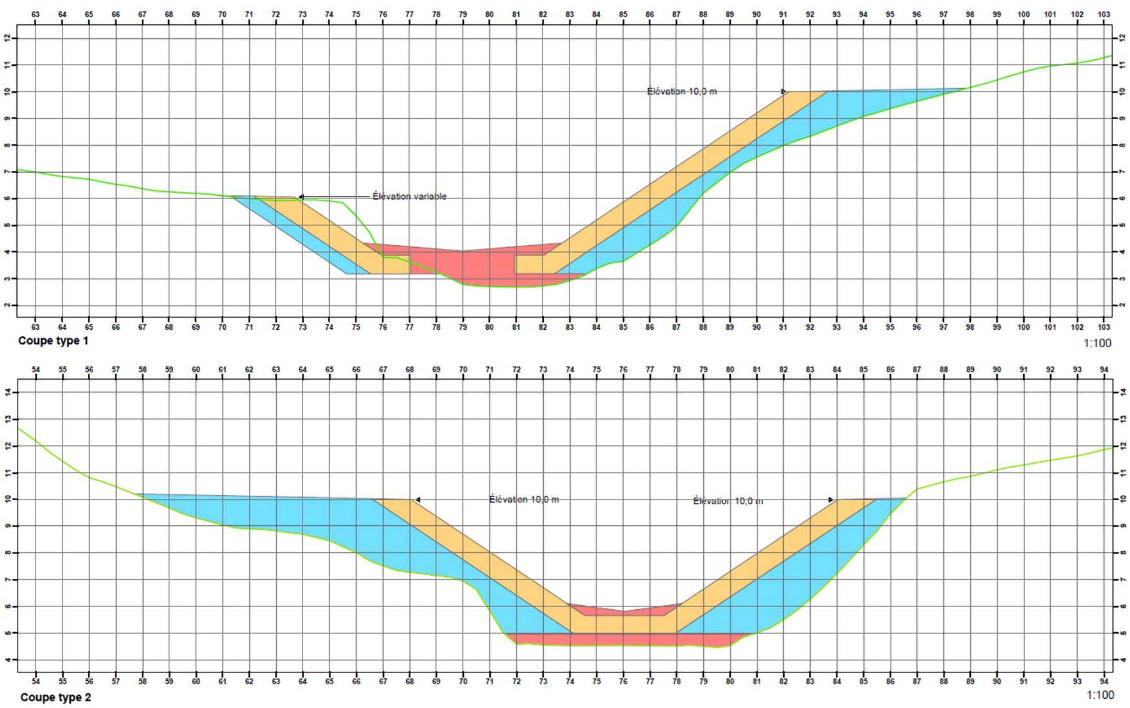


Figure 16 : Typical cross-sections of the design chosen for the prevention works on the À Veillet *River. Cross-section 1 (top): counterweight at one bank with erosion protection embedded in the opposite bank. Cross-section 2 (bottom): riprap counterweight at both banks. The blue colour corresponds to filter layer, the red to a material with a wider range of particle size graded, and the orange to riprap.*

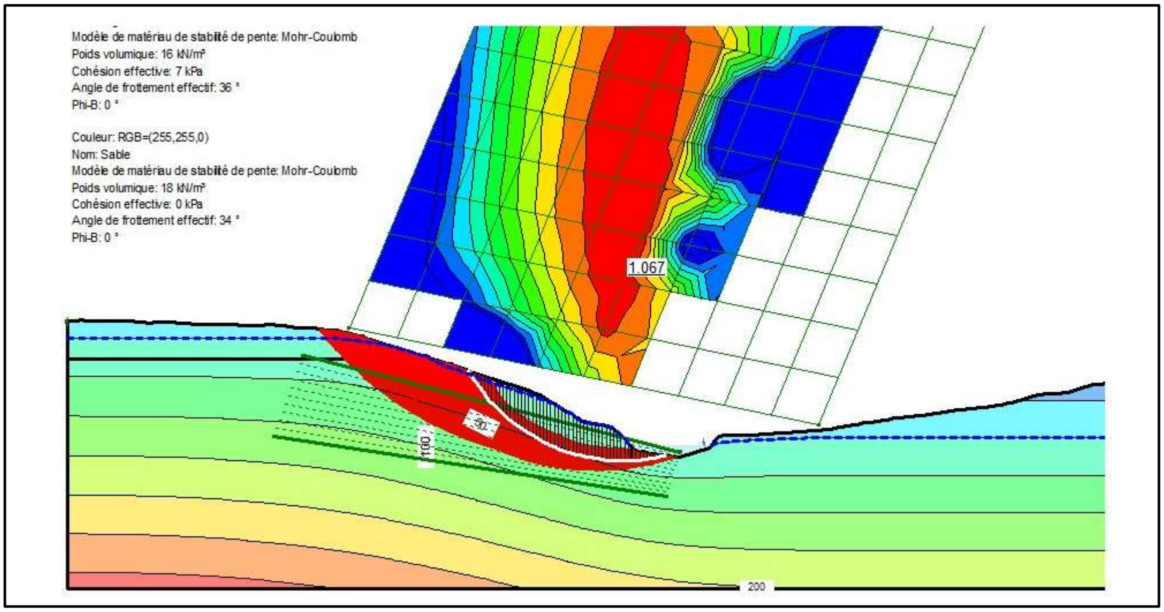


Figure 17 : Stability calculation for a slope with precarious stability and an alluvial plain on the opposite bank.

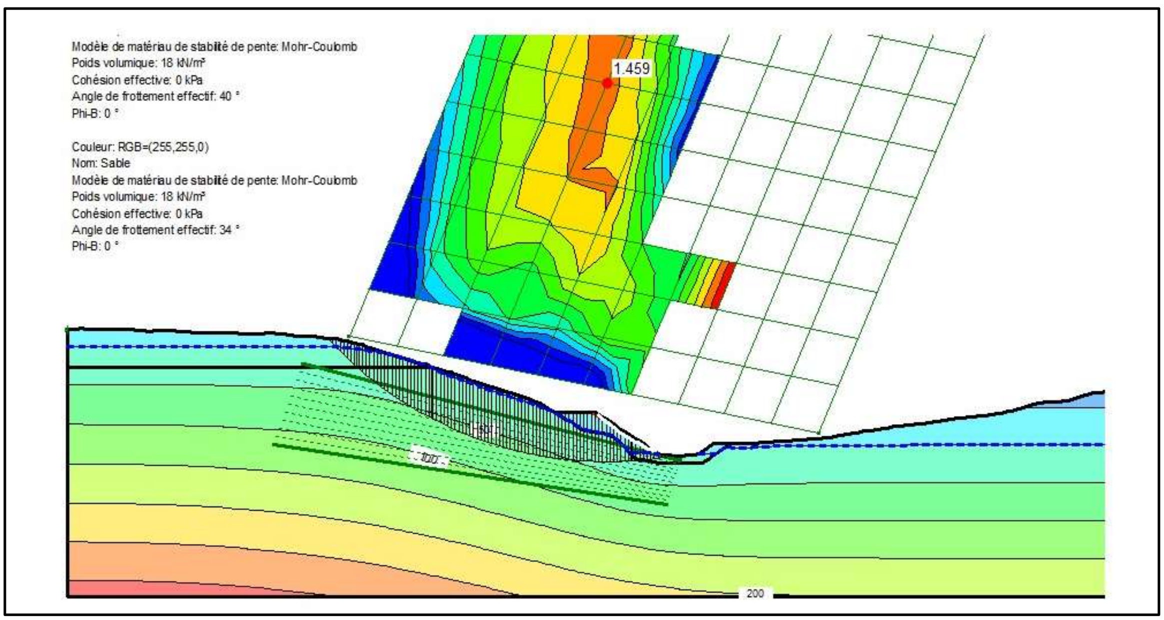


Figure 18 : Stability calculation to verify the benefits of implementing the chosen stabilization concept on a slope with precarious stability and an alluvial plain on the opposite bank.

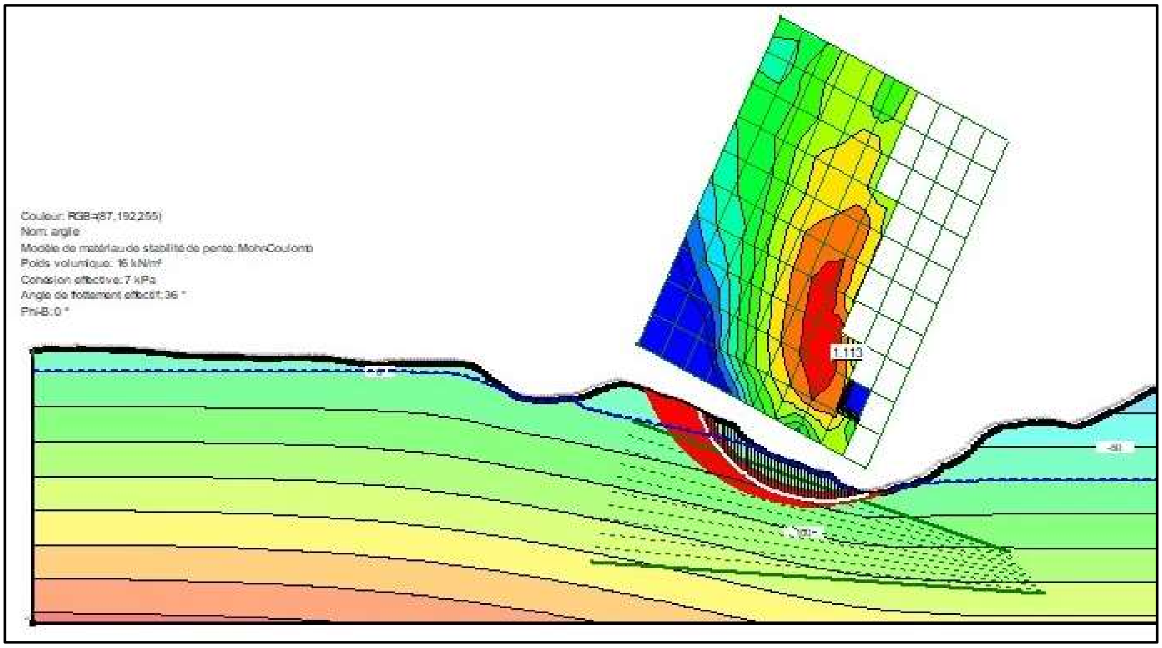


Figure 19 : Stability calculation for a slope with precarious stability without the presence of an alluvial plain on the opposite bank.

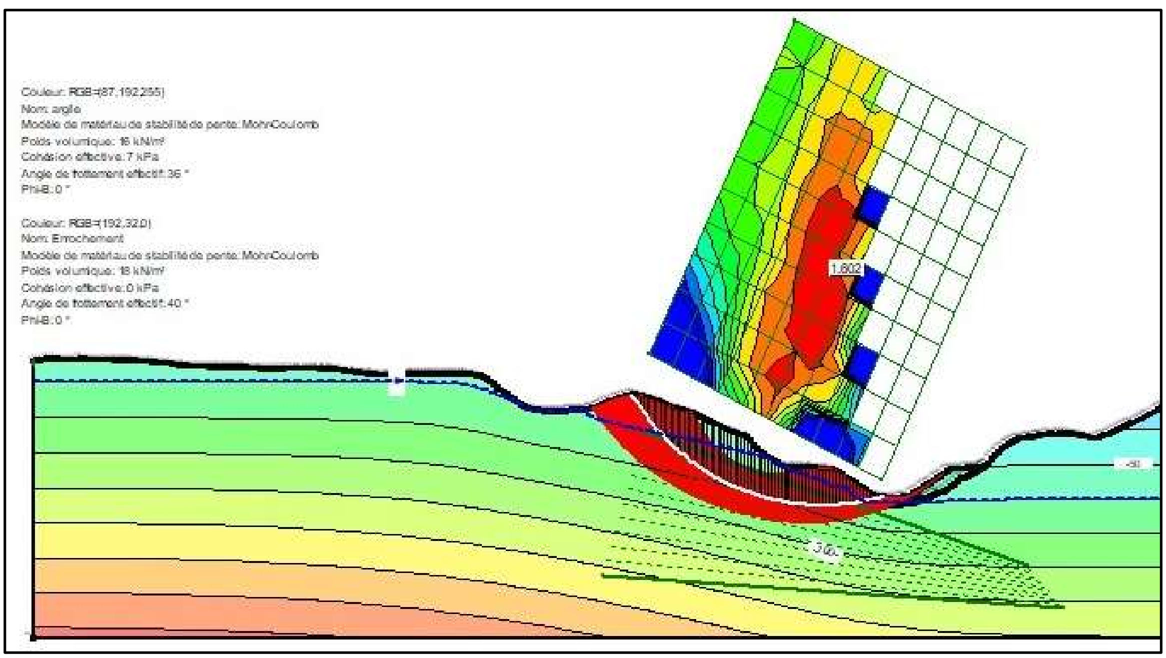


Figure 20 : Stability calculation to verify the benefit of implementing the chosen stabilization concept on a slope with precarious stability and no alluvial plain on the opposite bank.

Currently, the project has reached the stage of more actively involving members of the DEnv from the multidisciplinary committee and of incorporating elements into the design that will increase its environmental value. Here is a list of measures that have been decided upon or are currently under discussion regarding the environmental efforts being made to optimize the project:

- Use of a material with a wide range of particle sizes for the bottom of the reconstructed bed to prevent water loss through the riprap (material in red, Figure 16);
- Use of buried clay "ribs" in the design (Figure 21), in accordance with hydraulic recommendations, to force any water that may infiltrate the riprap to resurface. This method is inspired by similar work carried out in Norway (L'Heureux et al., 2025);
- Use of bioengineering techniques to control erosion in areas where the slope stability reserve is sufficient to avoid rock filling on banks that do not require it;
- Allow the raised riverbed to form a water retention area at the upstream end of the area to be stabilized to avoid having to install a long rockfill transition to reach the level of the stream bed and thus limit the rockfill area.
- Further meetings between the DGG, DH, and DEnv are planned to optimize the downstream transition and select the riprap concepts to be used on the tributaries of the *À Veillet* River, as well as specific measures to be included in the project that could serve environmental self-compensation purposes.

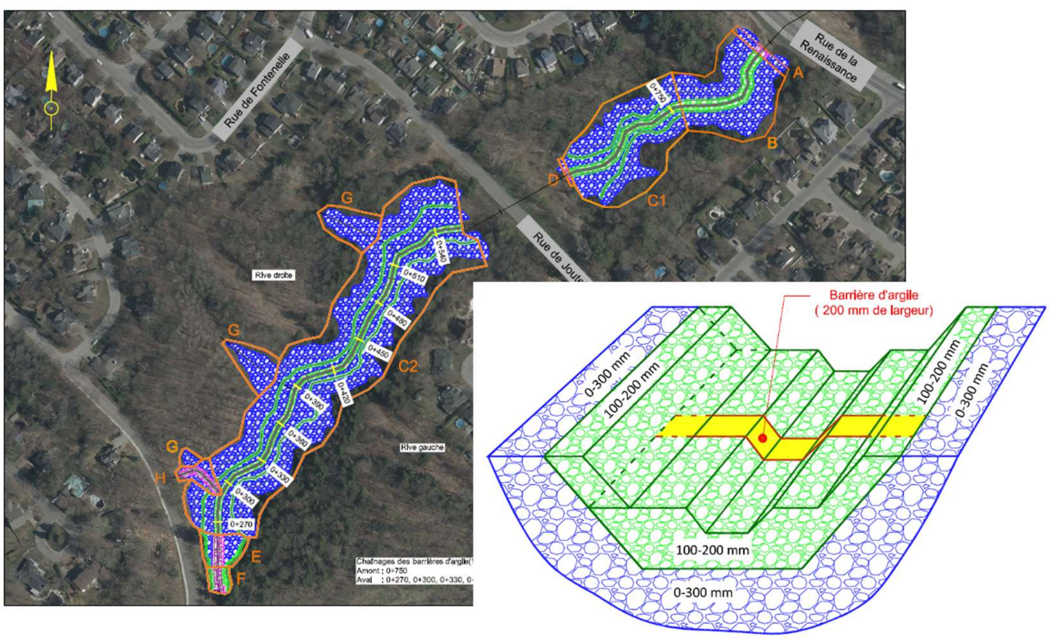


Figure 21 : Concept of clay "ribs" to create several thresholds along the design, to ensure permanent water flow over the stabilized riverbed (example of an MTMD project already completed in the past).

STOP 3 : Nicolet retrogressive landslide, 1955

Site history

The city of Nicolet is situated in a region where numerous landslides occur since its foundation in 1672. A total of 35 landslides were recorded between 1851 and 1975, including two fatal events. The one in 1955 and another one in 1869 resulting in four deaths.

The origins of the 1955 disaster date back ten years earlier, when the first landslide (rotational type) occurred at the site. Already, local authorities understood the threat this initial slide foreshadowed, as the mayor noted in a letter sent to the Commission des Eaux Courantes: "If the riverbed shifts in the spring as it has already begun to do, it won't be just the Fréchette garage that will disappears, but also the approaches to the Trahan Bridge, and possibly the school known as the Academie Commerciale, the cathedral, and the bishop's residence in Nicolet." (*Le Nouvelliste*, February 12th, 1947)

At that time, nothing was done. It was only when a new landslide, larger than the first, occurred on May 25, 1950, that first efforts to stabilize the banks were undertaken. Unfortunately, the first interventions only worsened the situation, and it was precisely when a large-scale stabilization project was launched that the tragedy occurred.

Landslide characteristics

The landslide occurred at approximately 11:40 a.m. on Saturday, November 12, 1955, and lasted for about seven minutes. According to Therrien *et al*. (2025a), the event was classified as a composite landslide. The movement was predominantly a flowslide with a spread component, as highlighted in the referenced study.

A testimony published in *La Presse* on November 14th gives us a clear understanding of how the events unfolded. "As I turned around, said Mr. Brassard, I saw the earth beginning to slide. Suddenly, Mr. Biron's gas station started to wobble, then tilted and vanished. [...] The pine trees in the grove began to slide toward the abyss. Thousands of tons of clay, soil, rock, and cement blocks tumbled down the slope like a true lava flow escaping from an invisible volcano. Then Mr. Biron's house collapsed, soon followed by the Academy, which began to disintegrate on the southeast side. I saw the ground sink foot by foot. After the homes of Drs. Georges-Étienne Roy and Moïse Vigneault met the same fate, everything seemed to return to normal. For two or three minutes, we saw absolutely nothing happen. We were still stunned when, suddenly, we saw the walls of the bishop's residence collapse."

An overview of the landslide and a view of the river facing upstream are presented in Figures 1 and 2, respectively. The width of the scar was measured at 125 m, with a retrogression distance of 198 m. The average depth of the failure surface was approximately 10.5 m, and the height of the backscarp, shown in Figure 3, was 6 m.

The total area affected by the movement was 21 307 m^2 (or 2.1 ha), involving an estimated 160 000 m^3 of displaced material. The debris propagation distance in Nicolet River, measured from the foot of the slope at the center of the slide, reached 300 m.

At the location where the landslide was likely triggered, the total slope height was about 16 m, and the natural slope angle prior to the event was approximately 23°. Aerial photographs taken before and after the landslide are shown in Figure 4.

Figure 1 : Overview of the 1955 landslide. Note on the right side of the photo the path leading to the toe of the riverbank, with a very steep slope. The riprap previously laid at the base of the riverbank is visible at the end of the debris on the right side of the photo. (Source : Gouvernement du Québec)

Figure 2 : View of the landslide looking upstream. (Source : Canada Wide Photos)

Figure 3 : Backscarp northeast of the scar. (Source : Canada Wide Photos)

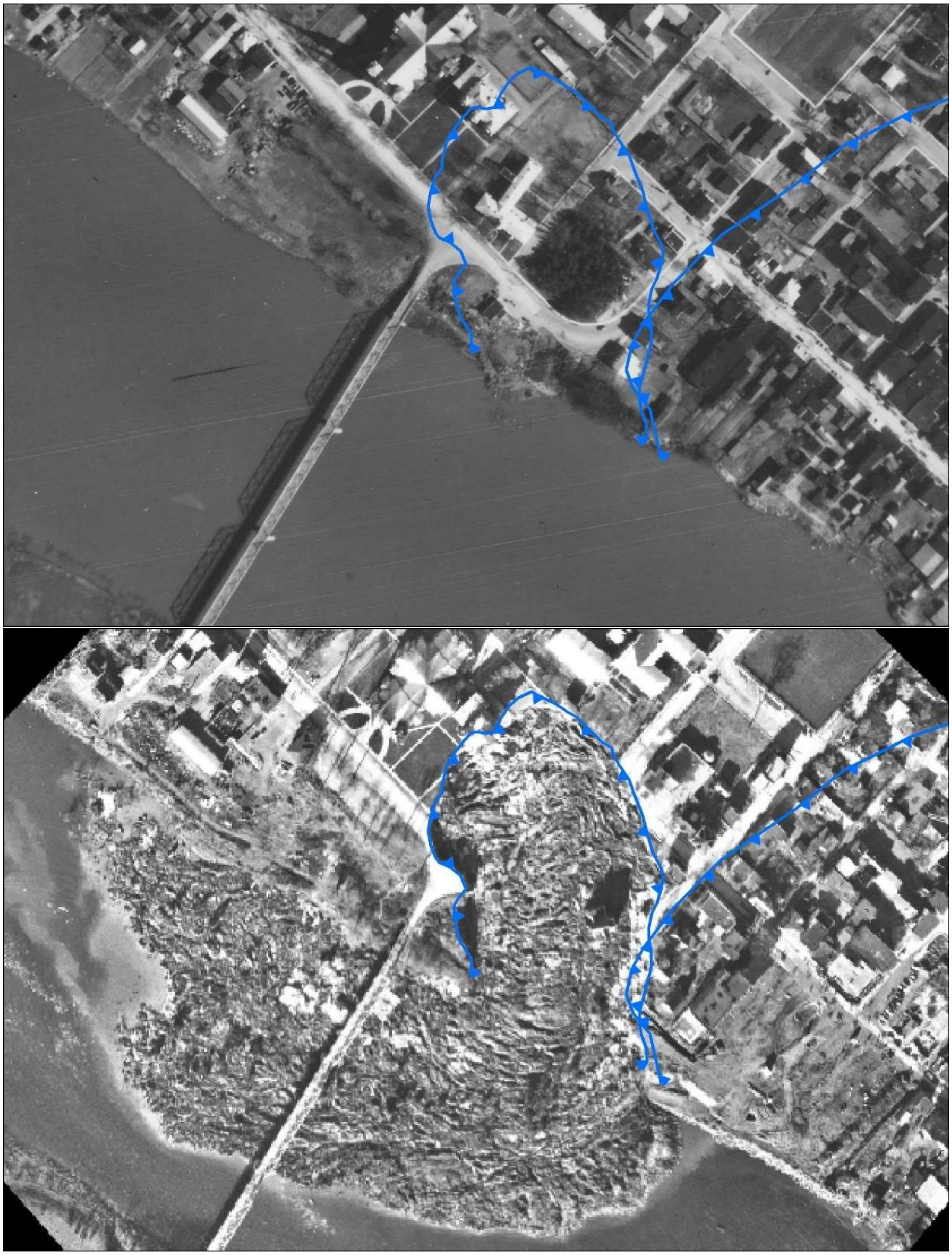


Figure 4 : Aerial photos before (1951) and just after the 1955 landslide. (Source : Gouvernement du Québec)

Damage caused by the event

The landslide had devastating consequences for both infrastructure and human life. Three lives were lost in the disaster and fifteen persons were injured. Among the affected buildings, two homes were completely destroyed, while a third home slid onto the debris but remained intact, as shown in Figures 5 and 6. A service station located within the affected area was also destroyed (Figure 7). The *Académie Commerciale* school was completely swept away by the movement. Fortunately, nearly 250 students had left the premises approximately forty minutes before the event and were scheduled to return one hour later for a movie screening, narrowly avoiding a greater tragedy.

Additionally, part of the bishop's palace was destroyed (Figure 8), and the cathedral, although not immediately demolished by the landslide, had to be demolished afterward due to structural damage sustained during the event. Total losses were estimated between 5 and 10 million dollars (equivalent to 58.5 to 117 million in 2025).

Figure 5 : Home built on a foundation raft that remained intact in the scar left by the landslide. (Source : Appartenance Mauricie, 3042-074)

Figure 6 : Homes destroyed or partially destroyed. Like in figure 1, note on the right side of the photo the path leading to the toe of the riverbank, with a very steep slope. (Source : Canada Wide Photos)

Figure 7 : Service station swept away by the landslide. (Source : Ministère des Transports et de la Mobilité durable)

Figure 8 : Bishop's palace partially destroyed by the landslide. Note the presence of a horst at the bottom right of the photo revealing the spread component of the landslide. (Source : Ministère des Transports et de la Mobilité durable)

Recovery

At the time, newspapers mentioned three possible solutions to permanently resolve the issue: 1. Divert the course of the river 2. Build a deep retaining wall along the river 3. Move the town back by half a mile. The solution ultimately adopted was to almost completely fill in the crater. The work was completed in June 1957.

However, rebuilding the road leading to the bridge proved more complex than expected. Minor new ground movements occurred during construction, but the bridge was once again accessible on December 26 following the disaster.

The event compelled the town to adopt an urban planning strategy and revise its regulations. The downtown area was completely reorganized. Main roads were widened and access to the bridge was cleared to improve traffic flow. Remaining buildings around the crater were either demolished or relocated. Ultimately, the site of the disaster was transformed into an urban park, after smoothing the scarps of the landslide scar and leveling the interior.

Geotechnical investigation

In the early 2000s, in order to update the mapping of areas prone to landslides, a series of boreholes and in situ tests were conducted by MTMD to characterize the soil in and around the landslide area. The locations of these investigations are shown in Figure 9.

Figure 9 : Location of the field tests.

Piezocone penetration tests (CPTU) were performed: one at the top of the scar (C31003-001-03), presented in Figure 10, and two others within the scar area (C31001-001-03 and C31072R-000-04), shown in Figures 11 and 12. In addition, two vane shear tests and two boreholes were carried out by Lefebvre (1974) to the west of the scar (Figure 13). Two vane tests and two boreholes were also performed by MTMD on the east side of the scar (F31003-002-05 and F31003R-006-05, Figure 14).

The stratigraphy observed in the area is typical of the Champlain Sea deposits. A surface layer of littoral sand approximately 2 meters thick overlies a sequence of marine clay. This clay exhibits a distinct change in properties with depth, characteristic of the region's sensitive clays. The upper clay layer is a uniform silty clay (approximately 70% < 2 µm), with traces of sand, a firm consistency, and medium to high plasticity and sensitivity. The lower portion of the deposit consists of silt and clay (approximately 40% < 2 µm), with traces of sand. Black spots characteristic of this clay were observed on the samples with a firm to stiff consistency, medium plasticity, and extremely high sensitivity. In the central part on the Champlain Sea basin, these two clay units are commonly separated by a thin layer on higher resistance, as pointed by J. Locat et al. (2021, 2025).

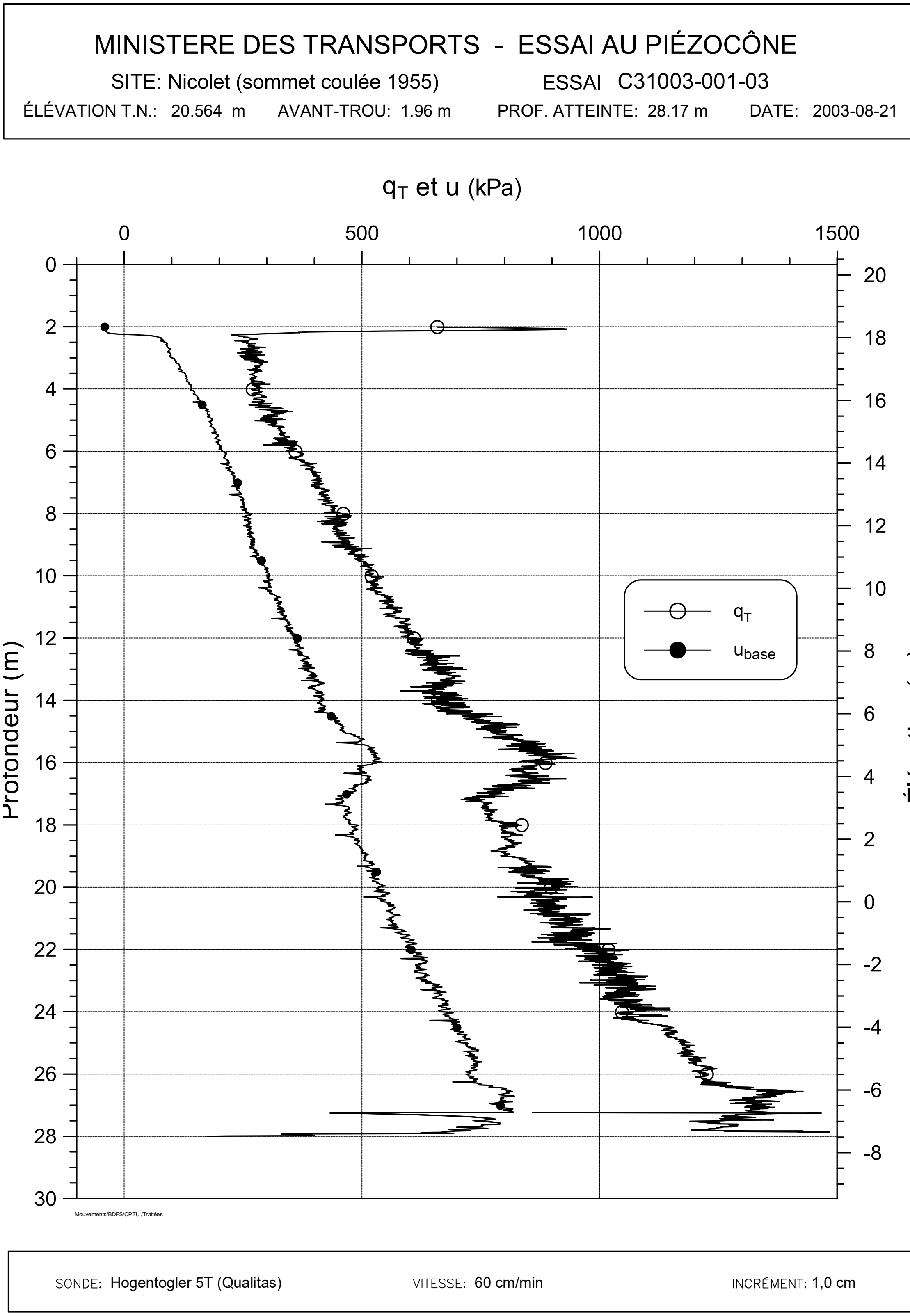
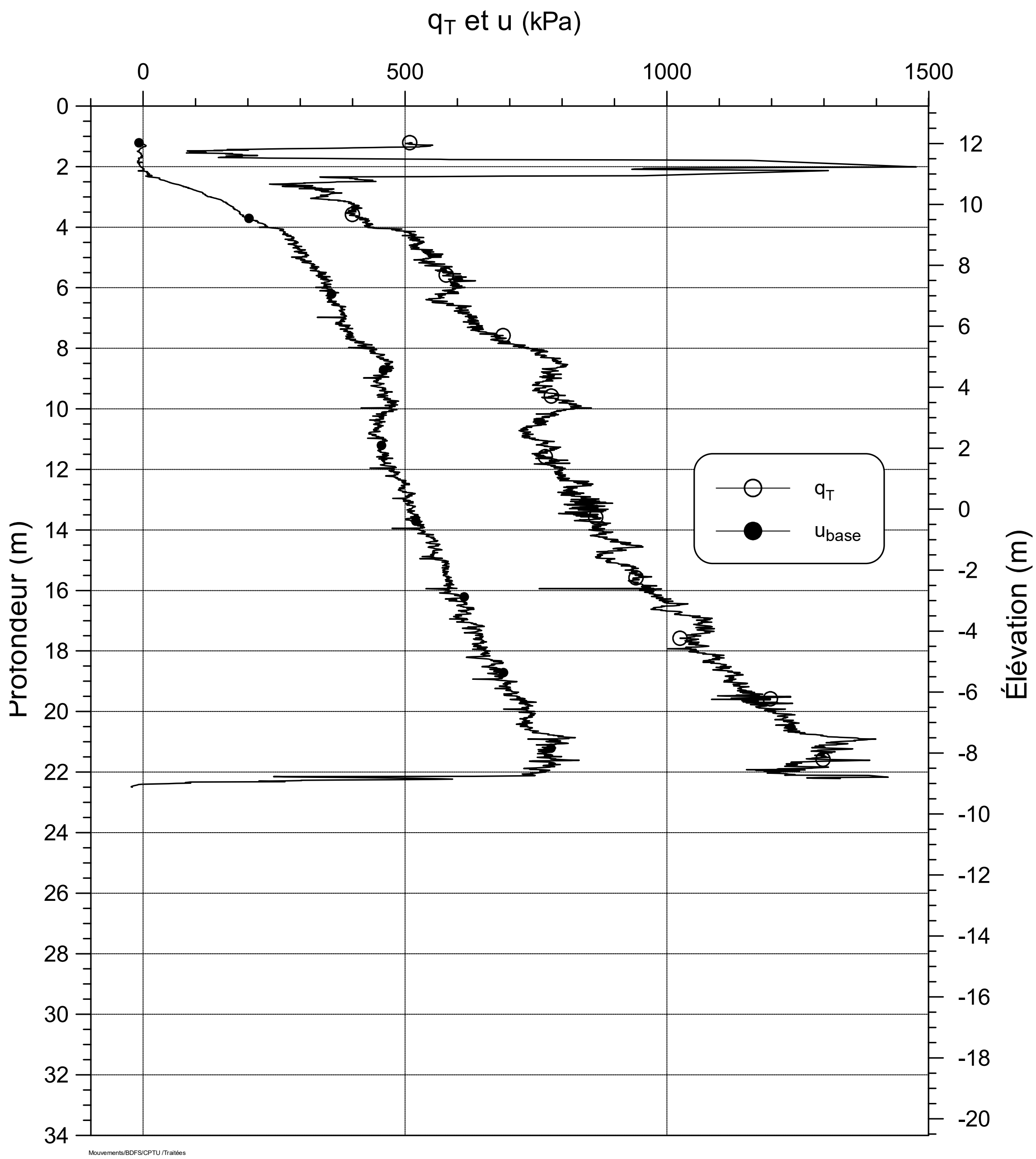


Figure 10 : Piezocone test C31003-001-03.

MINISTERE DES TRANSPORTS - ESSAI AU PIÉZOCÔNE

SITE: Nicolet (intérieur coulée 1955) ESSAI: C31001-001-03

ÉLÉVATION T.N.: 13.488 m AVANT-TROU: 1.68 m PROF. ATTEINTE: 23.08 m DATE: 2003-08-20



SONDE: Hogentogler 5T (Qualitas) VITESSE: 60 cm/min INCRÉMENT: 1,0 cm

Figure 11 : Piezocone test C31001-001-03.

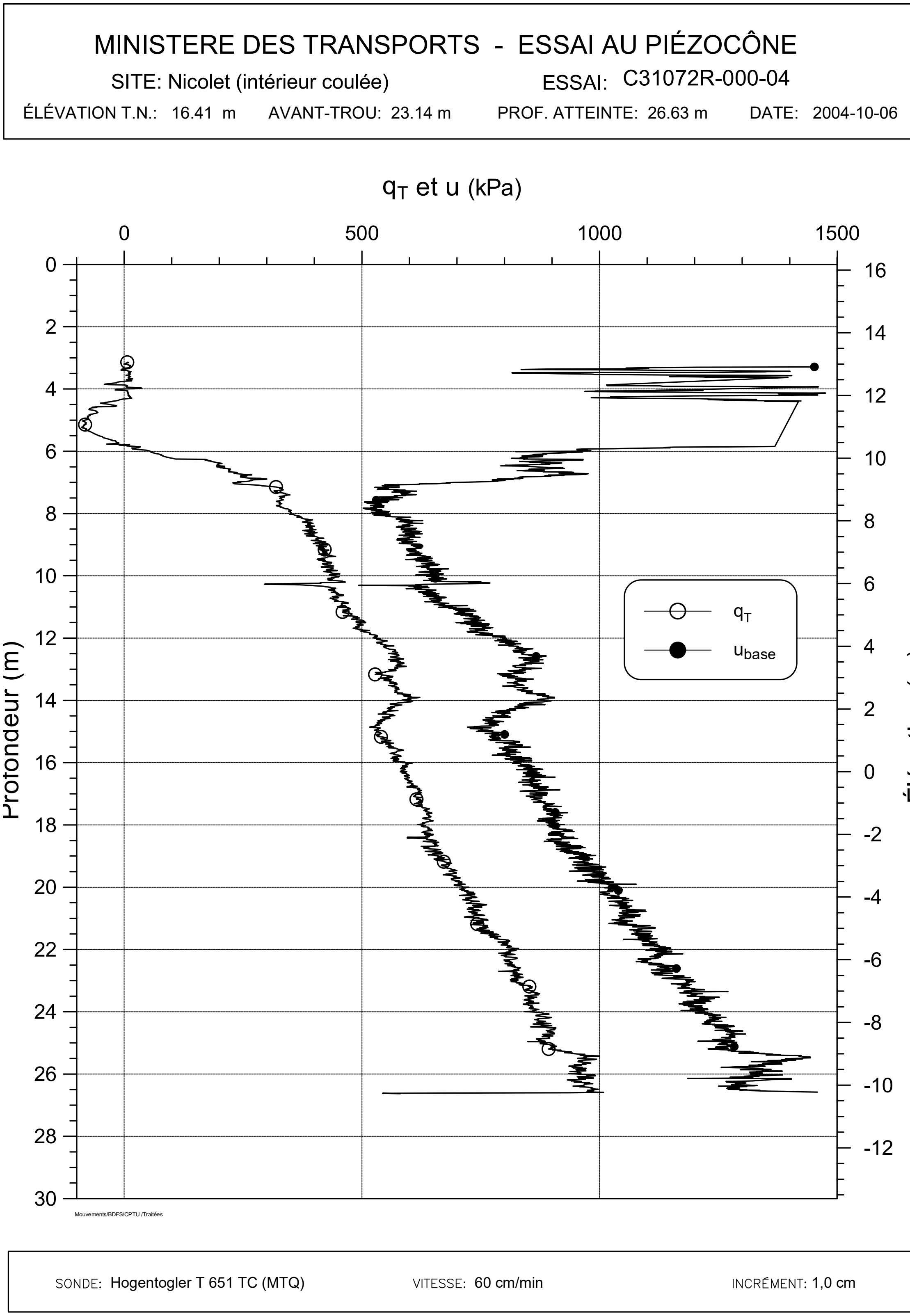


Figure 12 : Piezocone test C31072R-000-04.

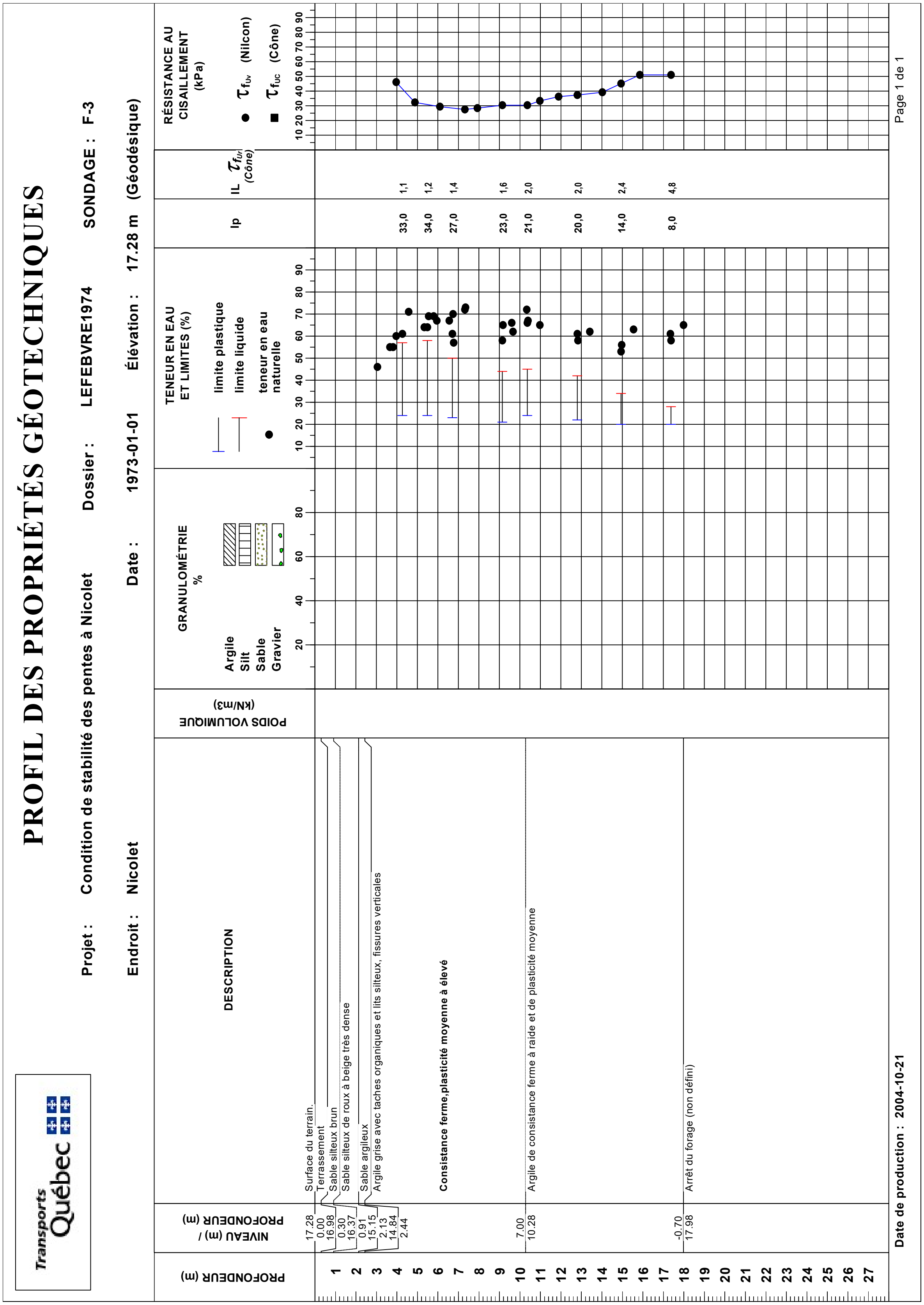


Figure 13 : Geotechnical profile (Lefebvre1974_F-3).

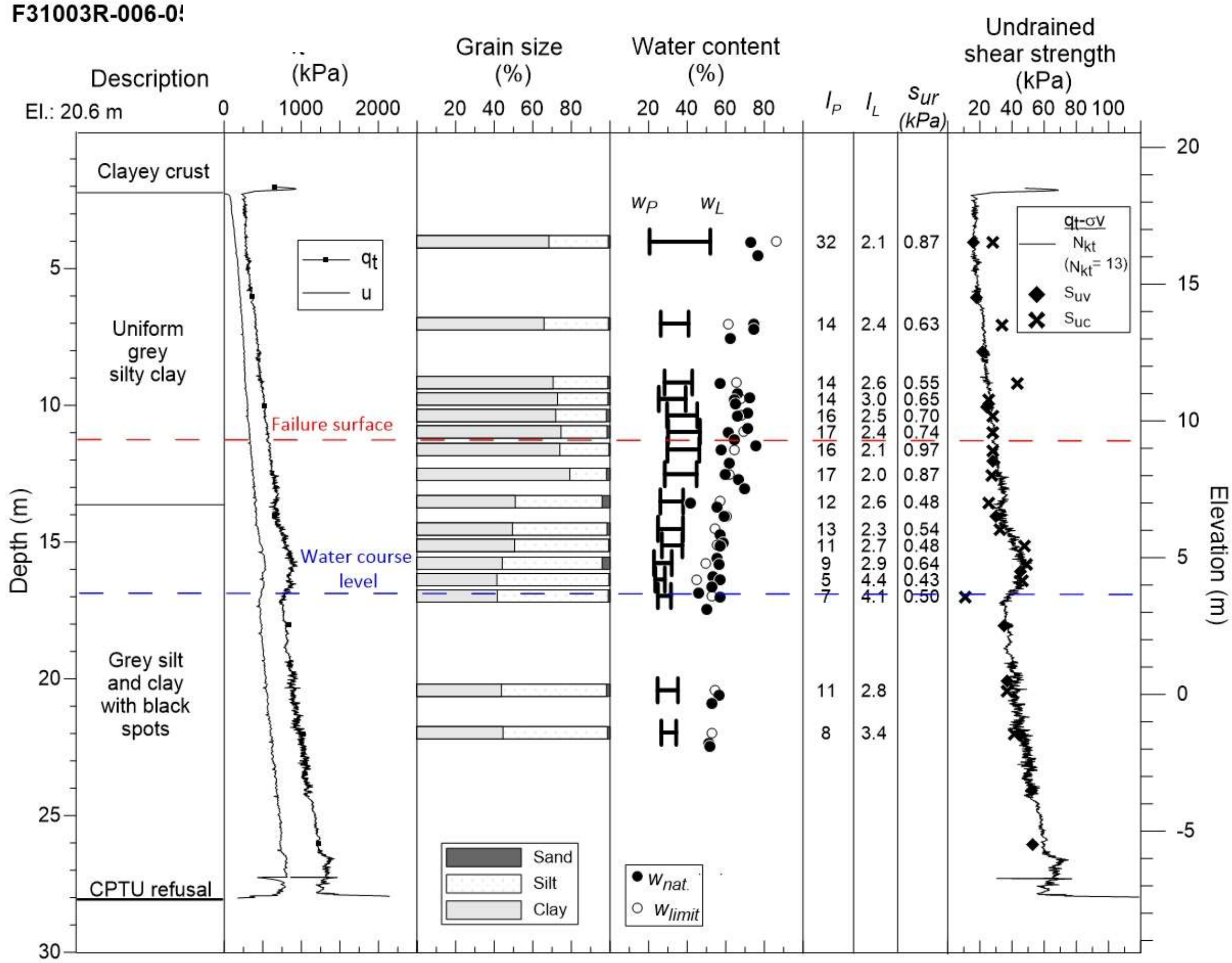


Figure 14 : Geotechnical profile (F31003R-006-05).

A firm substratum, possibly glacial till, was encountered at a depth of approximately 28 m at the top of the scar. This layer is believed to gently slope toward the river. Geotechnical properties of clayey soils are presented in table 1.

Table 1: Geotechnical properties according to borehole and vane test F31003-002-03.

Properties	**Elevation: 17 to 7 m**	**Elevation: 7 m to refusal**
w (%)	65%	55%
I_L	2 to 3	2.3 to 4.4
I_P	14 to 32	5 to 13
s_{ur} (kPa)	0.55 to 0.97	0.43 to 0.64
$s_{u\text{-}vane}$ (kPa)	18 to 44	37 to 48

Main stages of the movement

The location of buildings before and after the landslide is presented in Figure 15, providing insight into the extent of displacement and destruction. The initial failure likely occurred in the upstream part of the scar (Figures 16 and 17), at the site of a cutting made to install a riprap at the base of the slope (see on Figures 1 and 6). The first wave of debris, composed of soil from the slope and stones from the riprap (Fig. 1), was redirected after impacting the upwelling of the river bottom on the opposite bank, causing subsequent debris to flow downstream (Figure 18).

The next section mobilized was the part of the slope where the service station was located. The debris in this area must have been highly fluid, as the service station was dragged approximately 300 m downstream. This stage is typical of a flowslide. Following this, the pine forest and the *Académie Commerciale* school building were rapidly swept away. The final distribution of trees clearly indicates the direction of debris flow: some trees were displaced up to 350 m, while the school, which was completely destroyed, was carried 200 m, further confirming the high fluidity of the clayey debris.

The area of the scar continued to expand, but the travel distance of the debris decreased. This is evident from the 55 to 75 m displacement of homes located on the east side of the scar, as shown in Figure 19, which also depicts the debris and a completely destroyed home. The long travel distances of the school and pine forest debris suggest very high fluidity, and imply that a temporarily high backscarp may have existed before the final failures, which carried away the homes and the bishop's palace over shorter distances.

The landslide likely terminated on the west side of the scar, where only part of the bishop's palace collapsed, and the debris traveled less than 30 m. A historical photograph reveals a horst, indicating a spread component stage at the end of the movement (Figure 8). This mode of failure is also confirmed by an eyewitness account. Alphonse Boisvert, who was inside the academy at the time of the landslide: "As the ground flowed toward the river, the hole widened, quickly approaching the cathedral. I ran toward the front of the cathedral and the entrance to the bridge, and I was lucky enough to always stay just a few feet ahead of the precipice. At one point, the ground even collapsed on both sides, leaving a sort of point at the exact spot where I was standing, giving me just enough time to escape." (*La Presse*, November 14th)

The cessation of movement was probably due to the presence of fill to the north, associated with the street and bridge, and an insufficient critical height of the backscarp.

A cross-section illustrating the slope before and after the landslide, the stratigraphy, the position of the failure surface, the liquidity index, and the stability number as a function of elevation is presented in Figure 20. Based on the two piezocone tests conducted within the scar, the failure surface appears nearly horizontal, and the thickness of the debris increases toward the backscarp, ranging from 1 to 3.5 m.

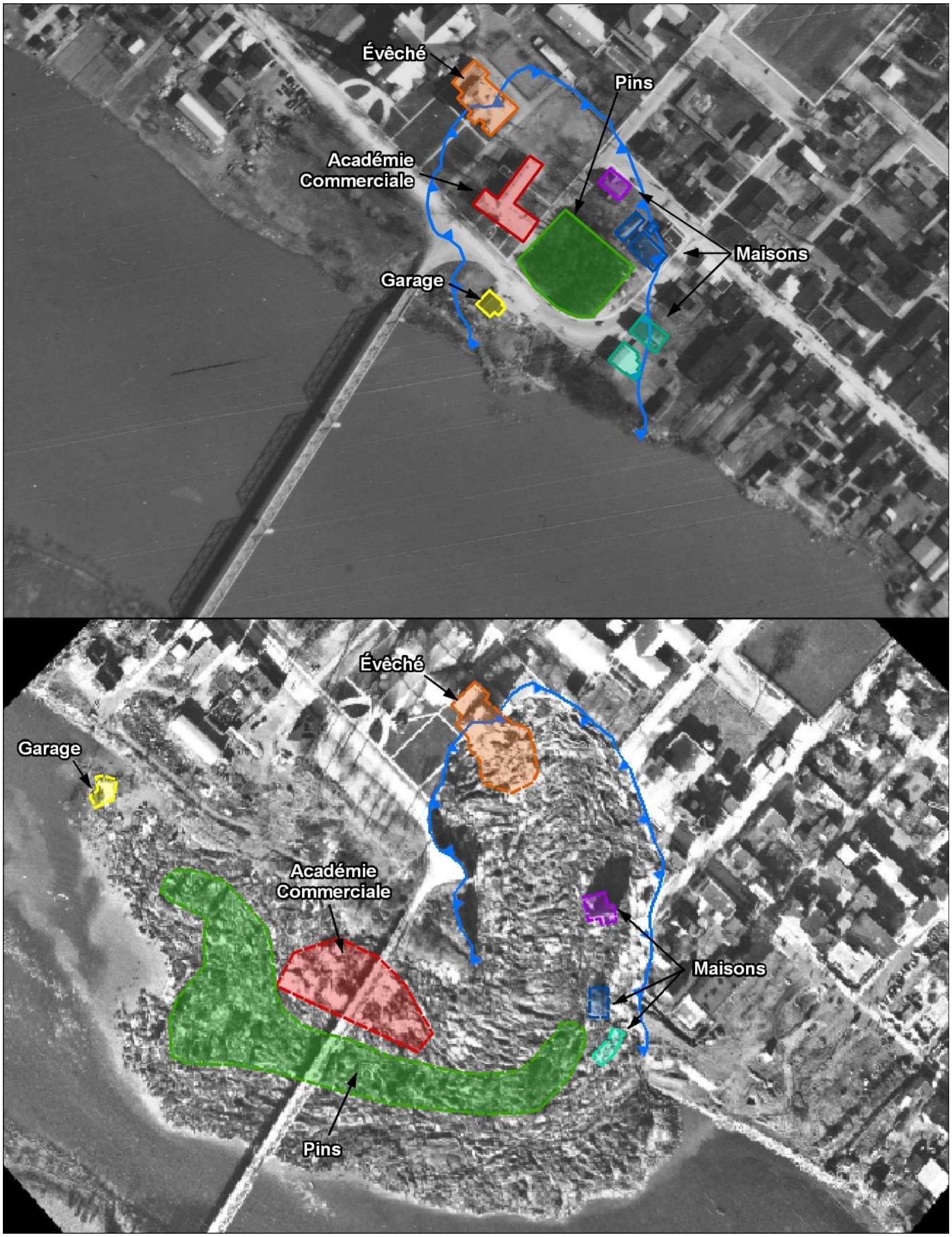


Figure 15 : Location of the buildings before and after the landslide. (Source : Ministère des Transports et de la Mobilité durable)

Figure 16 : Work in progress: riprap at the foot of the slope and cut in the slope. (Source : Ministère des Transports et de la Mobilité durable)

Figure 17 : Riprap upstream from the landslide and debris from the landslide. (Source : Ministère des Transports et de la Mobilité durable)

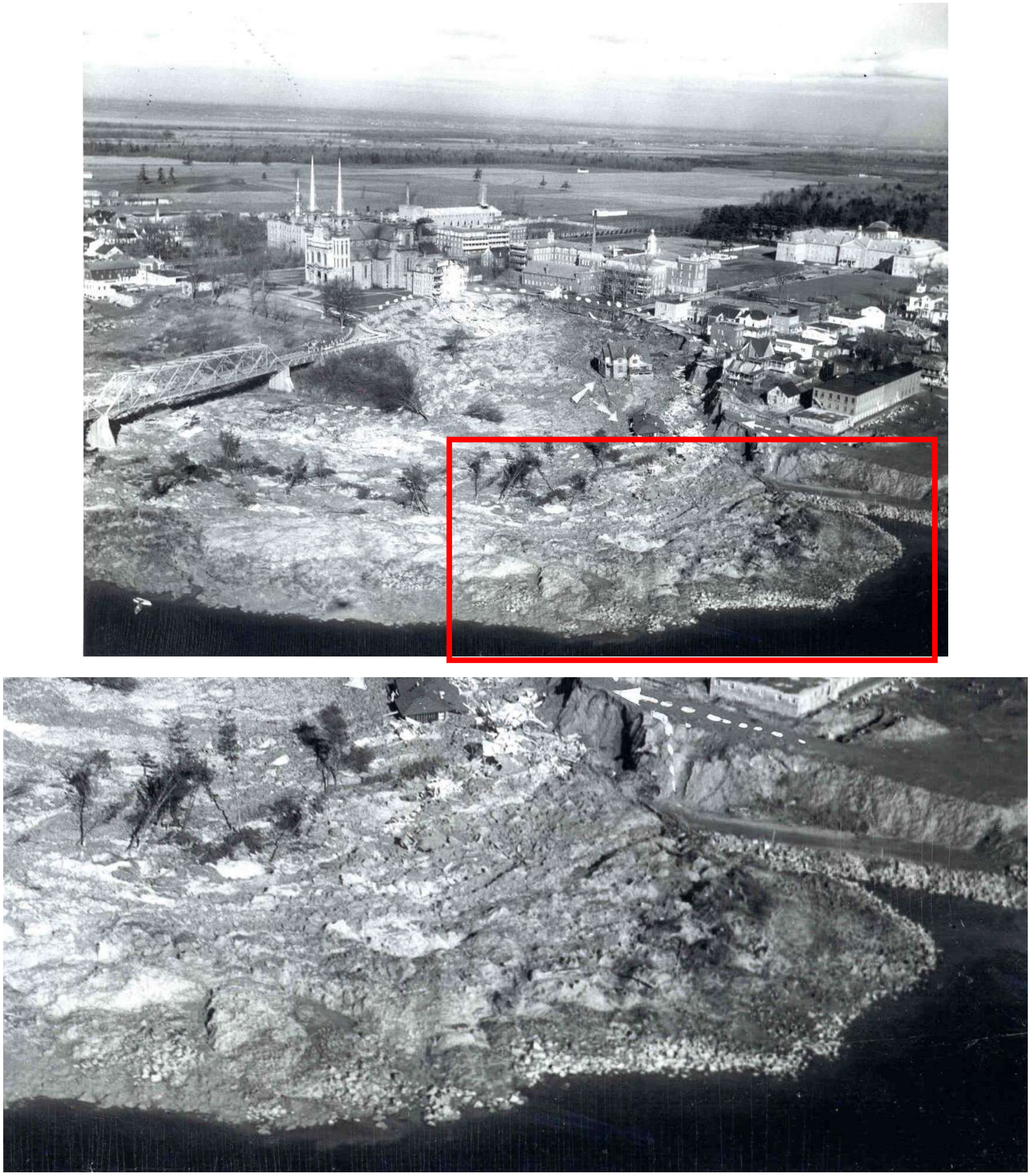


Figure 18 : Riprap swept away by the flowslide and cut in the slope. (Source : Gouvernement du Québec)

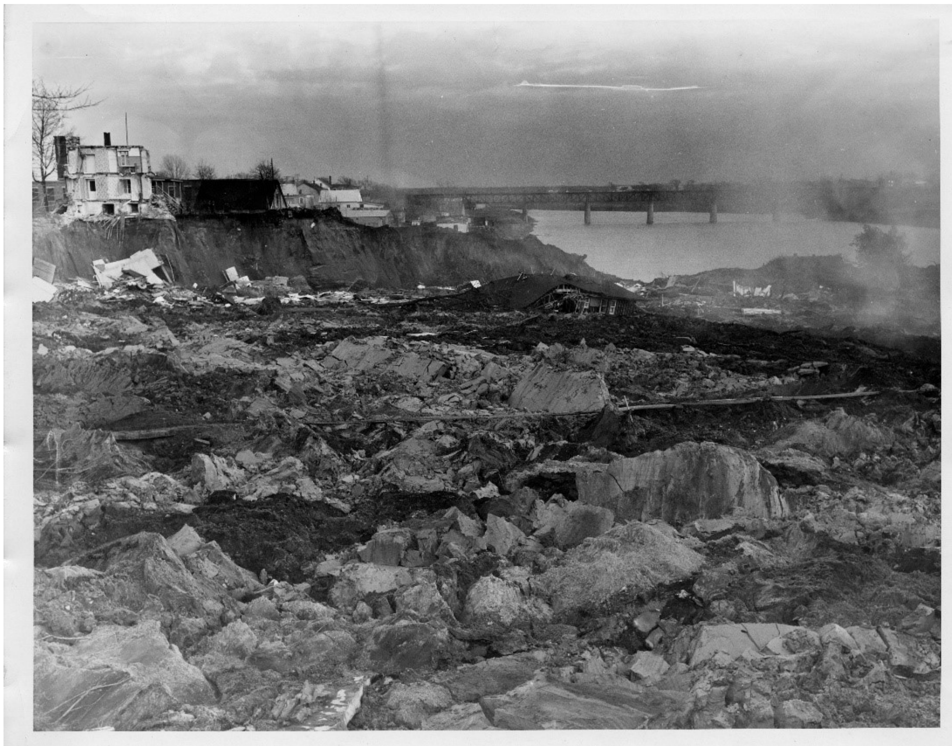


Figure 19 : Debris partially remolded in the scar. Two horsts are visible on the right side of the photo. (Source : Ministère des Transports et de la Mobilité durable, H. A. Beaudouin)

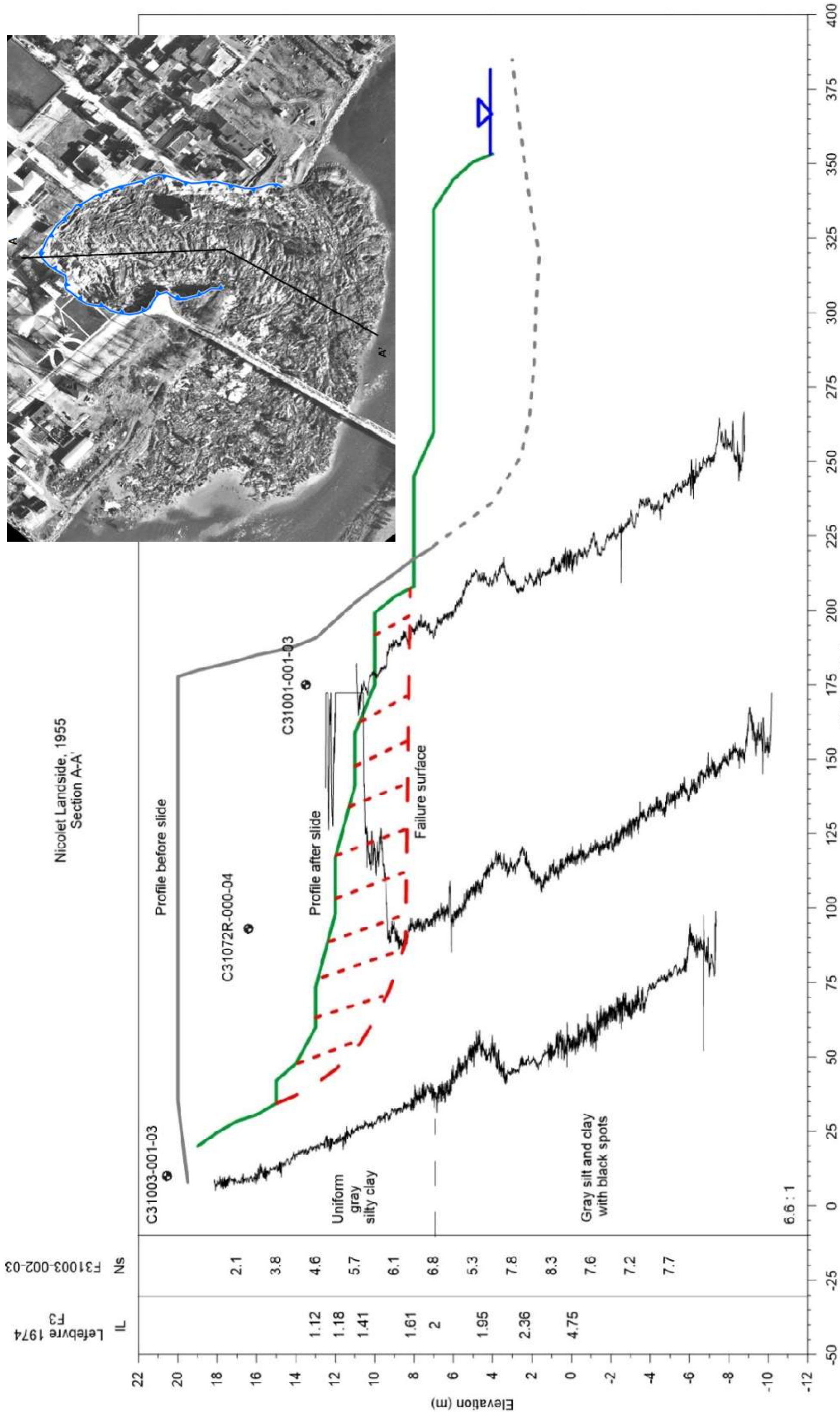


Figure 20: Section showing the slope before and after the landslide, the stratigraphy, the position of the failure surface, the liquidity index and the stability number depending on elevation.

Geotechnical characterization of the movement

Table 2: Characterization of the 1955 Nicolet landslide.

Characteristics	**Nicolet 1955**
Predisposition factors	- Presence of a very thick clayey deposit with homogeneous geotechnical properties. - Mechanical and physical characteristics favorable to the flow of debris according to the criteria of Lebuis *et al.* (1983) : S_{ur} < 1 kPa and I_L > 1,2. - Ns ≈ 6.1 at the failure surface and 6.8 at the foot of the slope (Figure 20). - Geometric conditions at the stability limit: slope 13 m high with an angle of about 23°. - Topography favorable to the discharge of debris.
Aggravating factors	- Water pressure probably high in the slope, attributable to heavy precipitation in the weeks preceding the event.
Triggering factors	- Excavation work in progress in the slope and at its base for installation of a riprap within the context of construction of a new road at the top of the slope (Figures 16 to 18). An excavator and two bulldozers were carried along in the landslide.
Revealing factors	- Presence of two previous rotational slide scars, including one occurring in 1950 (Figure 21). - Presence of retrogressive slide scars along the shores of the Nicolet River, including a 7.5 ha scar directly upstream from the site (Figure 22).

Figure 21 : Small-scale landslide in 1950. (Source : Ministère des Transports et de la Mobilité durable, Lucille Coulombe)

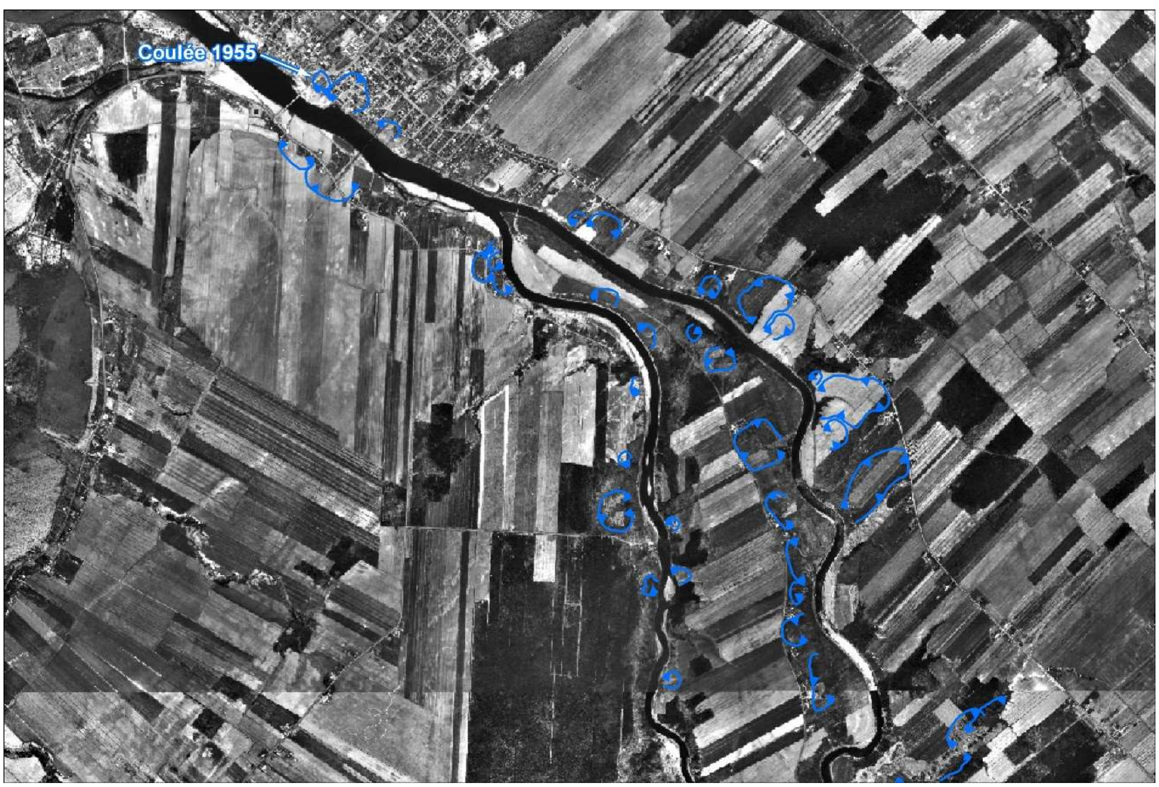


Figure 22 : Retrogressives landslides scars along the shores of the Nicolet and Nicolet Sud-Ouest Rivers. (Source : Ministère des Transports et de la Mobilité durable)

Stop 4 : Flowslide of Sainte-Monique

Introduction

On the morning of May 21, 2025, a major flowslide occurred at the head of an intermittent stream tributary to the Nicolet River, in the municipality of Sainte-Monique, 20 km south of Trois-Rivières (Figure 1). The event swept away a section of road, a residence, and two other buildings—a garage and a shed (Figure 1). Fortunately, the resident was able to leave the premises in time. Thanks to his intervention, the two neighbouring houses, located on either side of the landslide, were also evacuated.

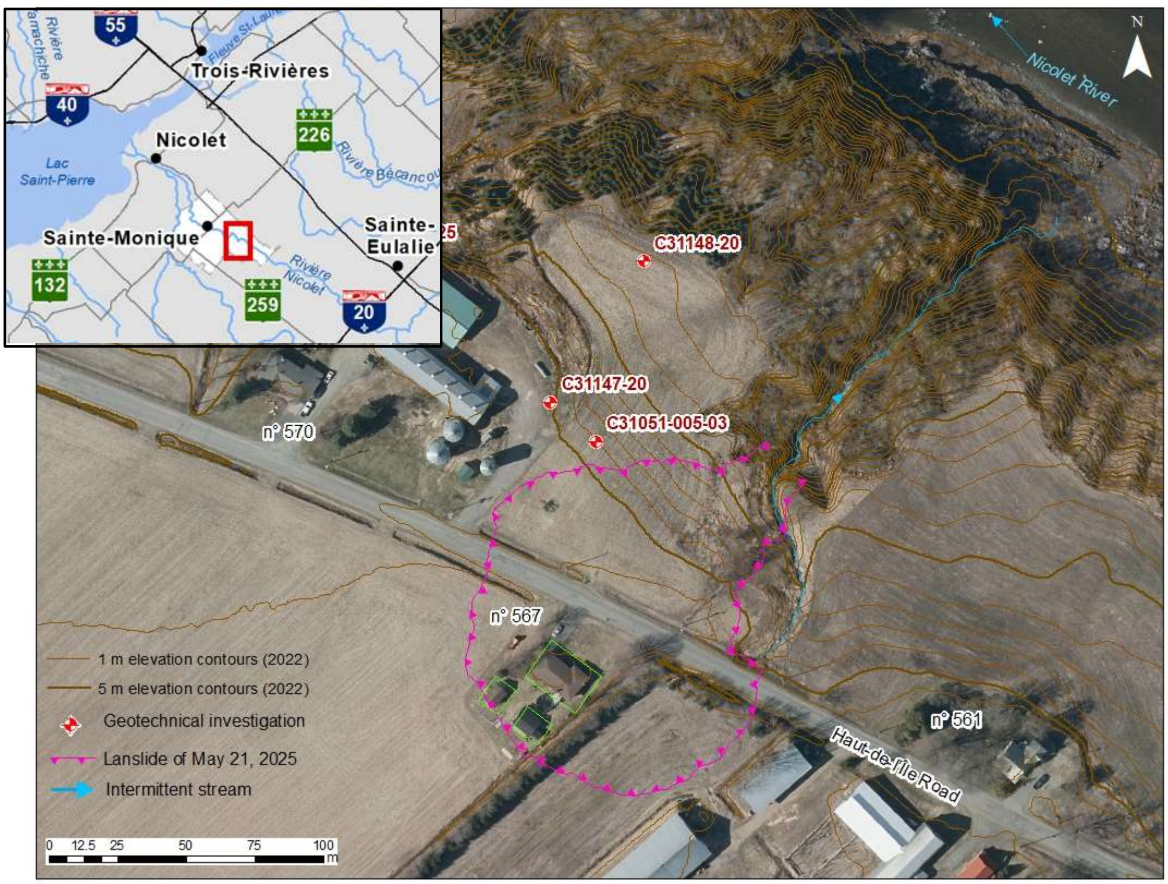


Figure 1 : Plan view on orthophotography background prior to the landslide, showing the landslide location and boreholes conducted in 2003 and 2020.

Site context and History

Bedrock outcrops locally along the banks of the Nicolet River in Sainte-Monique, but the region is primarily characterized by thick clay deposits, often overlain by a few meters of sand and gravel. Boreholes near the May 21, 2025, landslide site reveal a typical sequence: 2 m of surface sand, followed by 10-16 m of sensitive clay, and then a more resistant interglacial clay unit (predating the last glaciation) (Figure 2).

The landslide site is located on the left bank of the Nicolet River, at the level of a small unnamed intermittent tributary, mainly fed by a drainage ditch from agricultural lands to the southwest (Figure 1).

Lidar data from 2013, 2022, and 2024 show vertical incision of the ravine reaching about 2.5 m during this period in its deepest section (Figure 2). A comparison of 2013 and 2024 lidar data highlights regressive erosion, especially in the area where the landslide initiated (Figure 2).

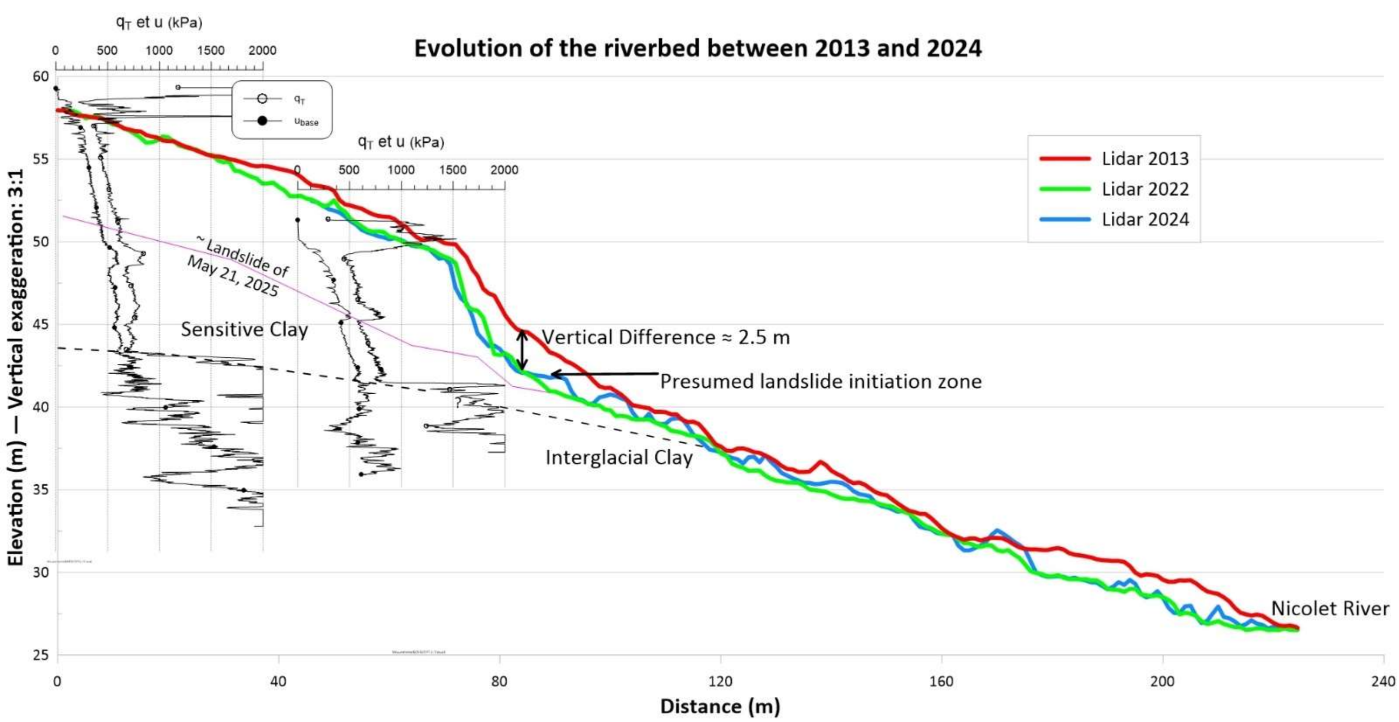


Figure 2: Longitudinal stratigraphic section showing vertical and regressive erosion in the intermittent tributary of the Nicolet River that led to the May 21, 2025 flowslide.

The presence of very sensitive clay in the upper layers makes the area vulnerable to large landslides. Several scars from highly retrogressive landslides are visible in Sainte-Monique and Nicolet municipalities to the north. Their retrogression reaches up to 500–700 m and they cover areas up to 40 ha (Figure 3). Notable events include the composite slide that occurred in downtown Nicolet in 1955 (Stop 3 in Figure 3), and three lateral spread landslides along the Siméon-Provencher stream in Sainte-Monique during the latter half of the 20th century (Figure 3).

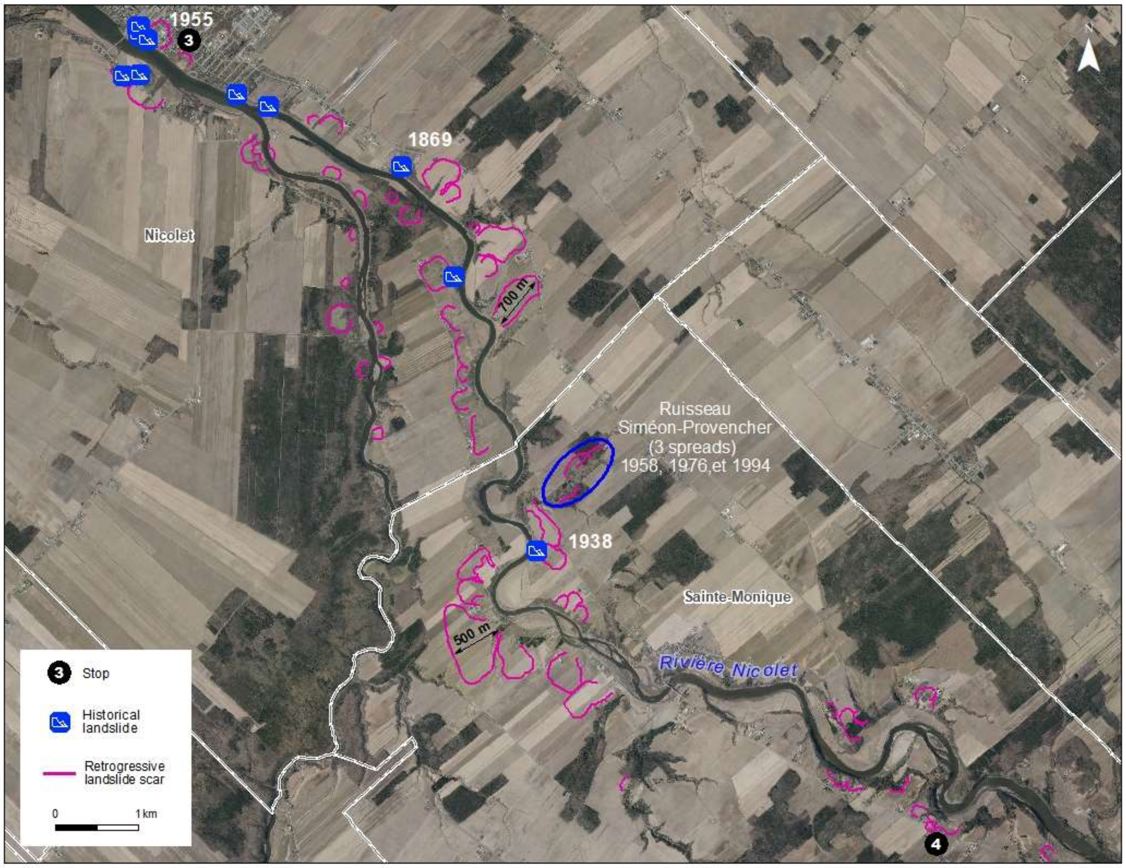


Figure 3: View of highly retrogressive landslide scars, some dating to the 19th or 20th century, in Sainte-Monique and Nicolet.

Just west of the May 2025 landslide, an undated flowslide scar of similar dimensions is visible (Figure 4). This older landslide began at the head of a neighbouring ravine in a similar geomorphological context. The similarity in location and scale suggests a shared dynamic related to ravine evolution and drainage conditions. These two head-of-ravine landslides represent a second generation of retrogressive failures, as both were initiated within an older scar likely triggered along the Nicolet River (purple dashes in Figure 4).

The May 2025 landslide occurred in a zone previously mapped as potentially exposed to highly retrogressive landslide hazards (MTMD, 2021), identified as "RA1top" in Figure 5. Active ravine erosion may trigger an initial rotational slide, and the presence of sensitive clays enables retrogressive movements.

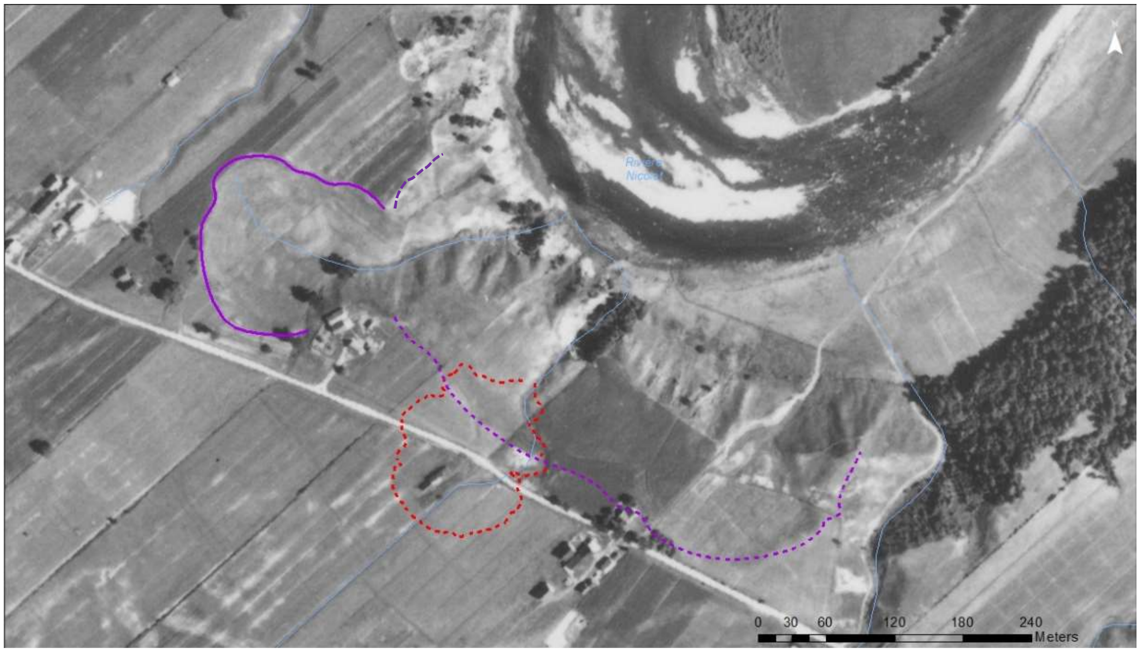


Figure 4: View of scars at the study site, including the May 21, 2025 event (red dashes) and the undated event in the neighbouring ravine (purple line) on a 1950 aerial photo. A first-generation undated huge scar (purple dashes) covers the downstream portion of both ravines.

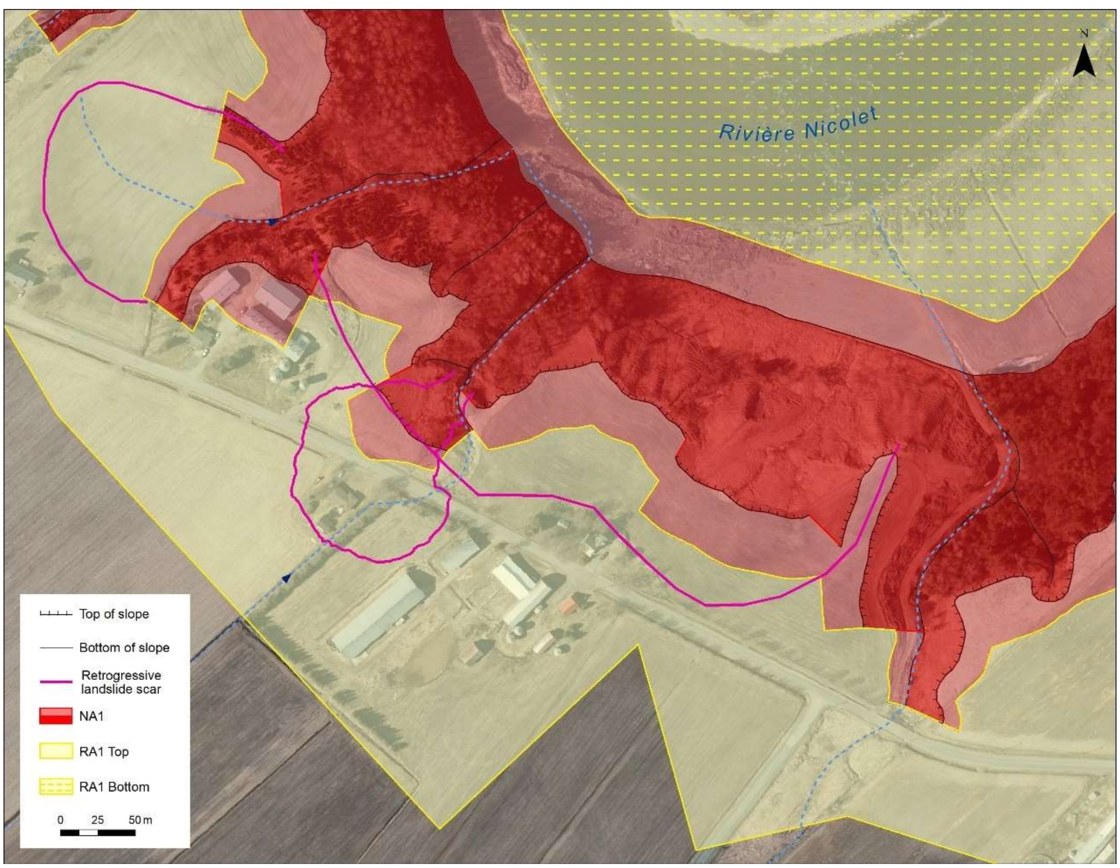


Figure 5: Excerpt from landslide hazard map# C31101-050-501_V2 (MTMD, 2021).

Rotational landslides were also observed along the ravine banks in 2006 and 2016 (Figure 6). These episodes reflect a common dynamic of slope movements linked to ravine erosion, which also led to the May 2025 flowslide.

Figure 6: View of the 2006 and 2016 rotational landslides.

Description of the May 21, 2025 flowslide

According to testimonies from nearby residents, a smaller landslide preceded the flowslide that occurred on May 21, 2025. This initial movement likely took place on the afternoon of May 20, just upstream of the 2006 landslide (Figure 6) and it reportedly stopped about 50 m from the road. The debris was likely significantly remoulded and reached the Nicolet River, leaving behind an unstable escarpment that may have contributed to the triggering of the subsequent major event.

On May 21, early in the morning, the flowslide occurred in two successive phases. The first phase, around 5:45 a.m., generated vibrations felt by residents of nearby homes. Alerted by the tremors, the occupant of the residence at No. 567 (Figure 1) quickly evacuated and warned his immediate neighbours. The landslide had then reached within approximately 15 m of the road. Shortly afterward, the landslide expanded, engulfing about 110 m of the *Haut-de-l'Île* road and the residence at No. 567, which was fortunately unoccupied at the time. The event affected an area of approximately 1.1 ha. Highly fluid debris reached the Nicolet River, leaving visible remoulded clay deposits up to 120 m upstream and 200 m downstream in the riverbed (Figure 7).

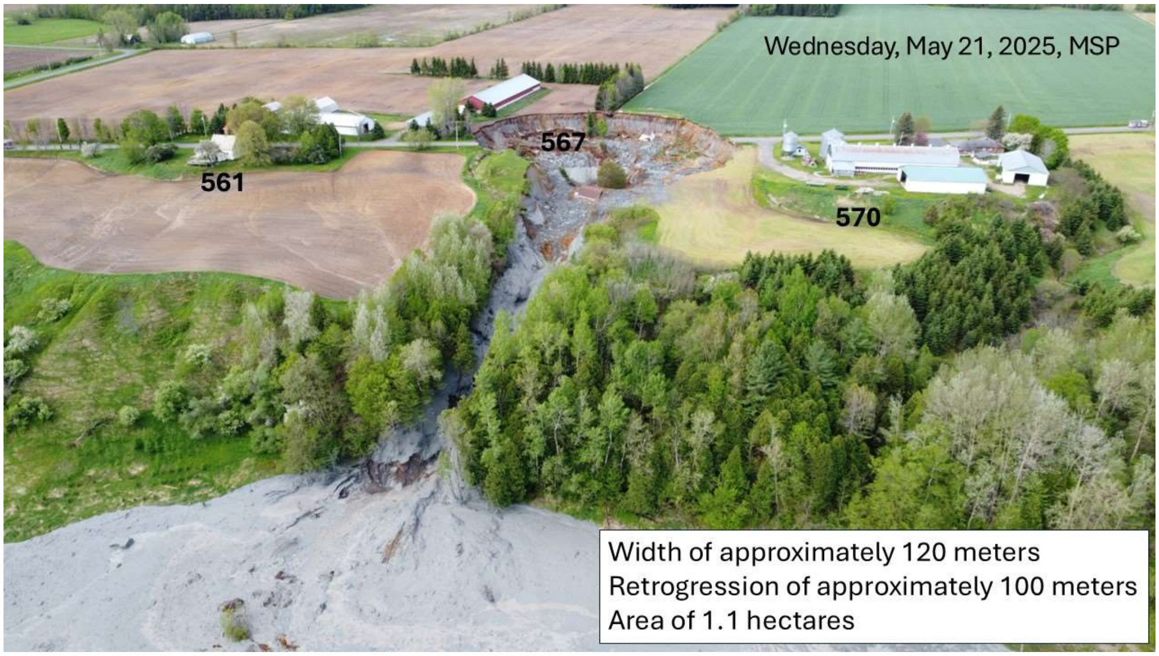


Figure 7 : Area affected by the landslide on May 21, 2025. (Source: Department of Public Safety (MSP))

From a geotechnical perspective, the flowslide occurred in two phases: an initial series of deep rotational failures originating from the initiation zone, followed by another series of failures located on an upper bench (Figure 8). These two phases left a deeper crater in the downstream portion of the landslide scar compared to the upstream portion, with an estimated height difference of 6 meters (Figure 8).

The first failure, associated with the lower bench, initiated in sensitive clay below the peak shear strength recorded by the piezocone in Figure 8b. In contrast, the second series of failures began above the resistance peak. This resistance peak observed in piezocone profiles is highly characteristic of Champlain Sea clays and is found throughout the St. Lawrence Lowlands. Below this peak, the clays are generally more sensitive and associated with a more leached zone (Locat et al., 2021, 2025).

The lateral scarps of the scar in its downstream portion reach the level of the lower bench (Figure 8a). They exhibit steep slopes ranging from 50 to 60°, with heights of approximately 12 to 14 m. In comparison, the escarpments around the upper bench reach a maximum height of 9 m. Given the instability and height of the downstream scarps, a 100-meter safety perimeter was established around the landslide to account for potential successive failures.

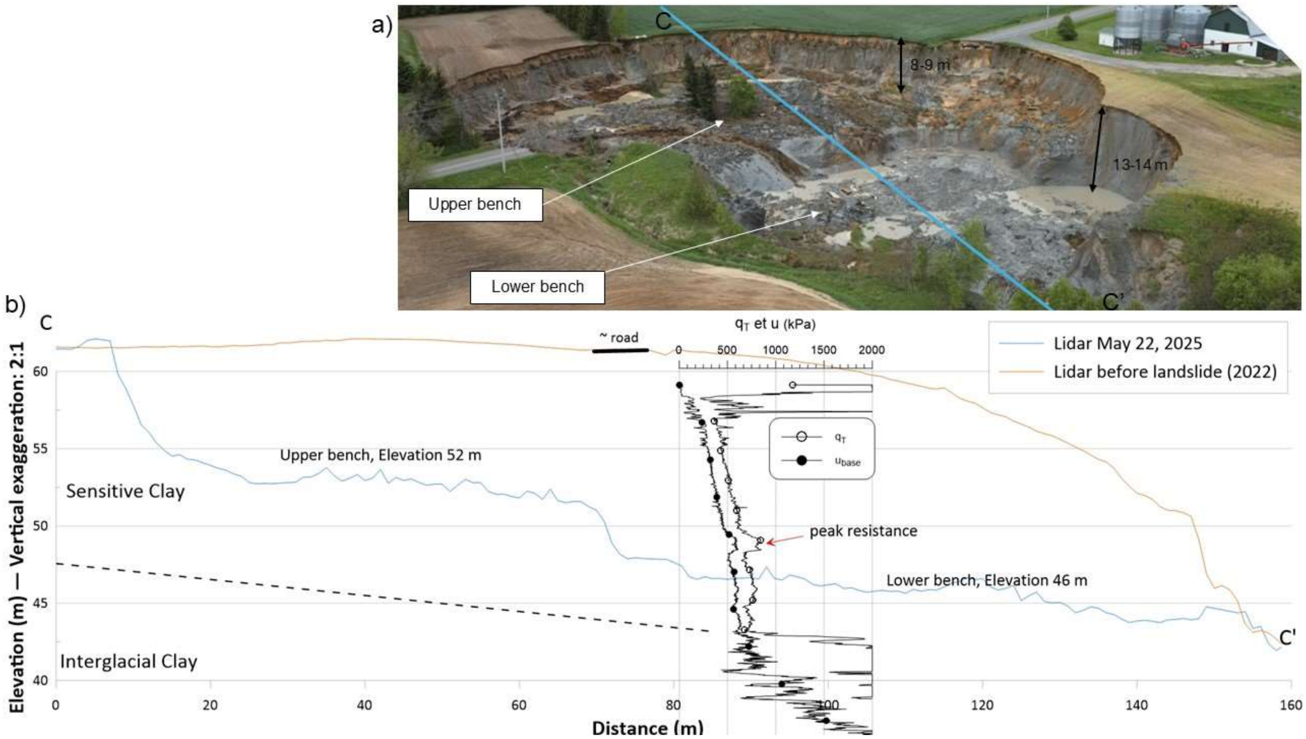


Figure 8: a) Drone photo taken on May 22, 2025 showing the western lateral escarpment and the upper and lower benches. b) Cross-section and values of tip resistance (qt) and pore pressures (u) recorded during sounding C31147.

In the first photos taken on the morning of May 21, the residence at No. 567 had already been entirely displaced outside the landslide scar, while its two secondary buildings (a garage and a shed), originally located side-by-side in the backyard (Figure 1), remained relatively intact and were still visible within the scar (Figure 9). The larger of the two (garage) quickly slid from the upper to the lower bench later that morning, while the smaller shed remained near its original location at the base of the rear escarpment (Figure 10).

Monitoring since May 21, 2025

Regular drone monitoring has been conducted since the landslide occurred on May 21, 2025. In the weeks following the event, the scarps of the scar progressively evolved, with most slopes becoming gentler. However, the lateral scarps flanking the lower bench—each approximately 14 m high—experienced significant retreat during the first two weeks, up to June 2 (Figure 11). Observations made in July and August indicated minimal changes to the scar's geometry. Nonetheless, two additional failures occurred in mid-September along the edge of the lower bench, confirming that the tallest scar walls remain unstable, and that debris continues to be subject to substantial remoulding (Figure 12).

Figure 9: Photo showing the position of the secondary buildings of No. 567 in the early moments after the flowslide. Note that the larger building near the center of the photo is still above the second bench. (Source: Journal de Montréal, May 21, 2025, 8:26 a.m.)

Figure 10 : Drone view showing the position of the secondary buildings of No. 567 around 8 a.m. on May 21, 2025. (Source: MSP)

Stabilization work for reintegration

In the coming weeks, excavation work will be carried out on the upper slope to mitigate risks associated with the escarpments of the landslide, particularly for nearby residences and buildings. These interventions aim to enable the safe reintegration of evacuated homes on both sides of the site and to facilitate geotechnical investigations within the scar. These studies are essential to assess the conditions for restoring traffic on the *Haut-de-l'Île* road.

Despite the planned work, the affected road segment will remain closed until further notice. The reconstruction of the road will depend on the depth of the crater formed by the flowslide. It will likely be necessary to revise the road profile or even consider a slight detour or a complete bypass of the affected area, depending on the results of upcoming geotechnical analyses.

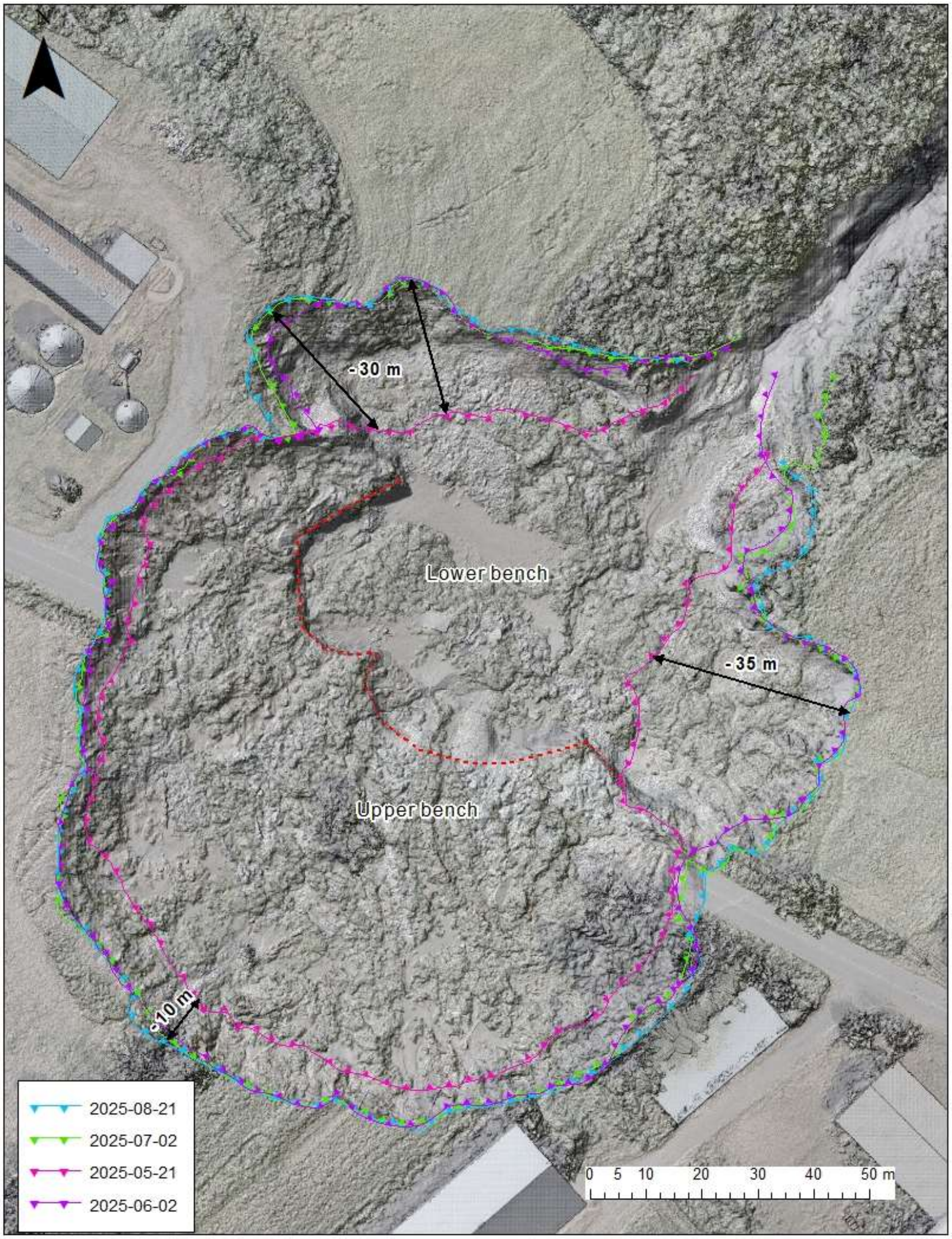


Figure 11 : Overview of the landslide scar at four different times showing evolution of its perimeter.

Figure 12 : Recent landslide (mid-September 2025) that toppled a utility pole. Note the significant remoulding of debris associated with this event.

Conclusion

The landslide that occurred on May 21, 2025, in Sainte-Monique highlights the vulnerability of the region to highly retrogressive landslides in the presence of sensitive clays. Although dramatic, the event shed light on complex and recurring geomorphological dynamics in an area already affected by previous slope instability events. The monitoring conducted since the event, combined with planned interventions, aims to secure the site, to allow for the safe return of evacuated residents, and to deepen the geotechnical understanding of the terrain. In the longer term, road reconstruction will need to account for the crater's morphology and the findings of future studies, which may lead to a revised road alignment. The rapid incision of the ravine, exacerbated by agricultural drainage, is a contributing factor to the site's evolution and must be considered in future planning. This recent case highlights the technical, human, and territorial challenges associated with this event, while providing an opportunity to deepen our knowledge and optimize our practices.

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APPENDIX

INFOCLIP 1 : The Saint-Alban landslide of April 27, 1894[2]

The landslide that occurred on April 27, 1894, along the Sainte-Anne River, a few kilometers upstream from the village of Saint-Alban, is by far the largest historical case in Quebec. It covers an area of approximately 420 ha (Figure 1). By way of comparison, the second largest historical landslide is five times smaller than the Saint-Alban landslide, about 78 ha, and occurred in 2022 along the Swamp River, a tributary of the Petite-Rivière-à-la-Baleine in northern Quebec (Fournier et al., 2022). The 1971 event in Saint-Jean-Vianney, which caused 31 deaths, covered an area of 32 ha (Demers et al., 2021).

According to an analysis of archival documents, lidar data, and recent geotechnical investigations, the 1894 movement in Saint-Alban occurred in several stages (Figure 2), involving different failure mechanisms: flowslide, spread, and slab sliding, especially. The nearby presence of the Saint-Narcisse moraine, a large deposit of highly draining juxtaglaccial materials, generated strong interstitial pressures in the adjacent clay deposit, facilitating the leaching of salts from the interstitial porewater and greatly increasing the sensitivity of the clay (values exceeding 1000 were measured in the lower parts of the clay deposit). However, the moraine also controlled the retrogression process, which ultimately came to a halt at its flanks.

Despite a retrogression distance of approximately 1.4 km and a width of 3.6 km, this cataclysm only affected a total of six residences and their outbuildings, as it occurred in a sparsely populated rural area. It also caused only four deaths. In addition, a few buildings, including two residences, were swept away by a huge slab of undisturbed land and remained perfectly intact, despite being displaced by approximately 1.4 km. Their residents thus survived the landslide. Furthermore, the flow of debris from the landslide caused enormous disruption and damage along the Sainte-Anne River to the St. Lawrence River, over approximately 40 km (Figure 3), sweeping away a few road bridges along its path. The debris and waters released by the sudden drainage of a huge temporary water retention eroded the banks downstream in several places and caused other landslides along the Sainte-Anne River in the days that followed, as far as the village of Sainte-Anne-de-la-Pérade, about 40 km downstream. At this location, seven houses and five barns were swept away, while three other residences were demolished preventively, and three others were relocated.

In several places, the river changed course, and sedimentation from debris even connected some islands at its mouth to the mainland. Sedimentation and water turbidity also disrupted navigation, fisheries, and drinking water supplies for riverside villages for a very long period.

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[2] The information provided in this capsule is taken from Paradis et al. (2025) paper, presented during the workshop IWLSC-2025.

All these impacts probably make this event the largest historical ecological disaster caused by a landslide in Quebec.

Although a landslide of this magnitude remains an extremely rare event, its relative contemporaneity, in geological terms, also reminds us that such an enormous event is still possible in the geological context of Quebec.

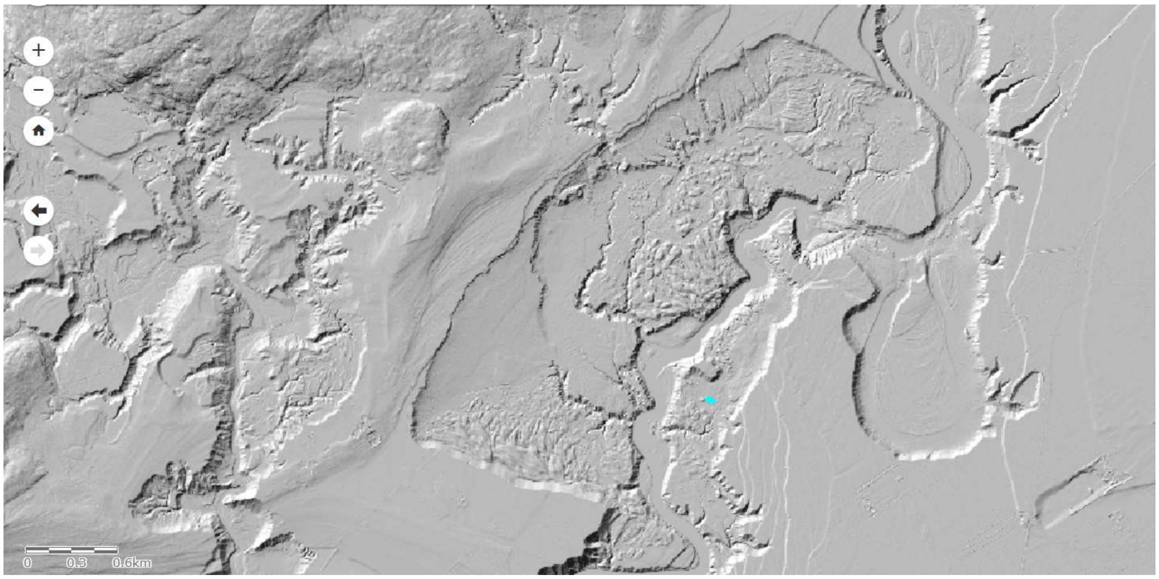


Figure 1 : Hillshade relief of the scar left by the 1894 landslide in Saint-Alban. The Saint-Narcisse moraine forms a linear protuberance running along the northern part of the scar.

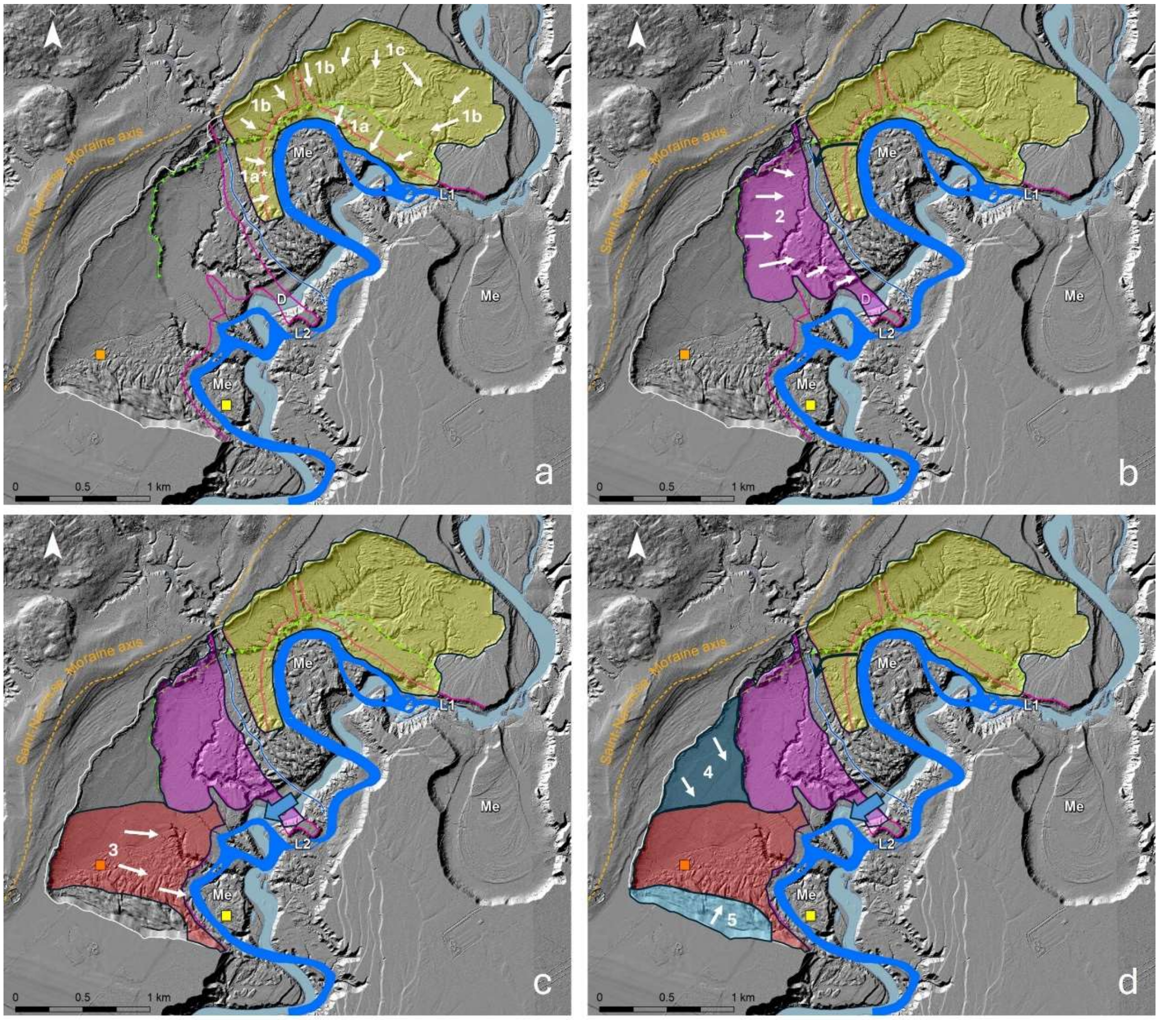


Figure 2 : Main stages of the 1894 landslide (see Paradis et al. 2025 for details).

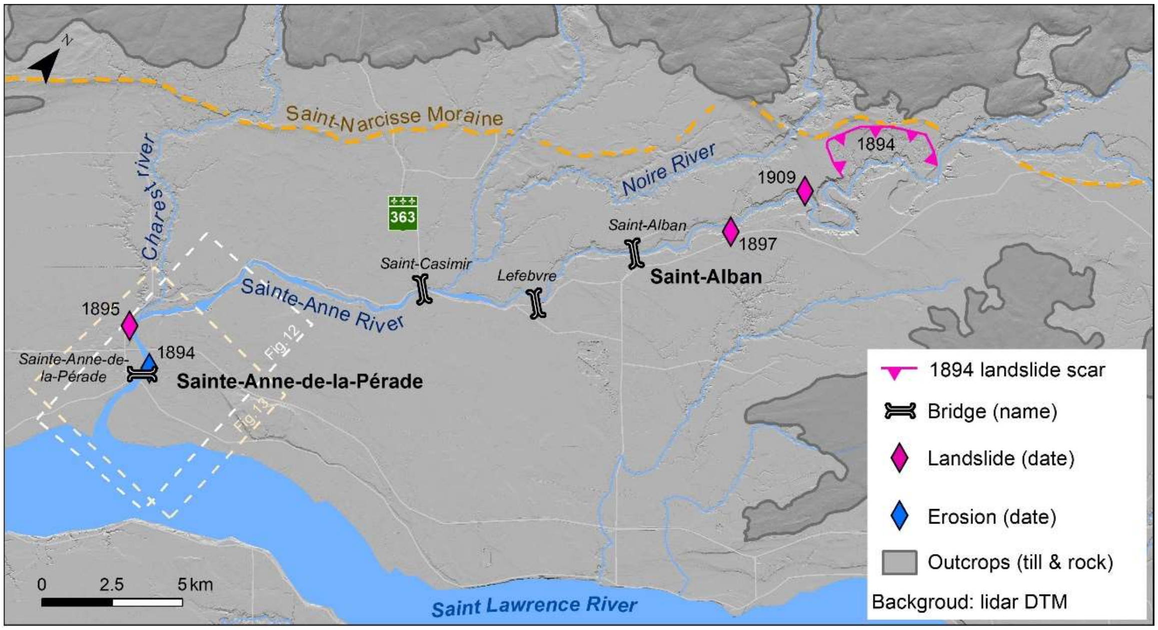


Figure 3 : Overview of the main impacts caused by the passage of landslide debris and flooding along the Saint-Anne River to its mouth at the Saint Lawrence River.

INFOCLIP 2 : Study for a residential development in Saint-Alban

A geotechnical study was undertaken in 2023 in the municipality of Saint-Alban, where a proposed new residential development was located partly in an area that had been mapped in the 1980s as potentially prone to highly retrogressive landslides (HRL). Since this area also encompassed a large portion of the village that had already been built up (Figure 1), a more detailed analysis was conducted to assess the danger to the village and to determine whether a zoning update was necessary.

Few surveys and boreholes were carried out in the 1980s (those identified in yellow in Figure 1), and zoning was mainly based on observations concerning the nature of the riverbank and the size of old scars left by highly retrogressive landslides along the Sainte-Anne River. In the vicinity of the study site, there are only three scars along the course of this river, all located upstream of the village (Figure 2). The first, located 3.1 km away, dates to 1897 and has a retrogression distance of approximately 225 m. The topographical features within this scar, as well as an archive photograph, suggest that this landslide was a spread (Paradis et al. 2025). The second scar, located 4.1 km away and of unknown date, is very elongated but narrow, with a retrogression distance of approximately 1.3 km. This shape strongly suggests that it was a clay flow. The third and last is the mega-scar dating from 1894, the largest of all historical cases in Quebec, with multiple rupture modes (see previous capsule and Paradis et al. 2025).

The designers of the 1980s mapping based their dimensions on an approximate average of the first two scars, excluding the last one given the specific geological context of this site. The setback distance used for zoning the area was therefore around 800 m. (yellow area in Figure 1). However, the height of the slopes was originally much greater at the sites of these three scars (approximately 30, 34, and 55 m, respectively) than at the site under study near the village (14 m). Furthermore, the extent of the clay sensitive enough to undergo a clay flow-type landslide, allowing such a large distance of regression to be reached, had not been surveyed at the time.

A detailed investigation campaign was therefore undertaken in 2023, including seven new piezocone soundings and as many boreholes with sampling (numbered 27062 to 27068 in Figure 1). This investigation identified the presence of several geological units of varying thickness and nature (Figure 3). A layer of sand, up to nearly 10 m thick, forms the first unit beneath the natural ground surface. The second underlying unit consists of interbedded clayey and sandy strata, varying in thickness from approximately 2 to 4 m. This is followed by two relatively uniform layers of clay, the first of which is stiffer and more overconsolidated than the underlying layer. The upper layer varies in thickness from approximately 6 to 8 m and forms the lower part of the slope bordering the river at the study site (Figure 3, borehole 27062). The second of these clay units is 3 to 6 m thick and lies below the water level of the Sainte-Anne River. All piezocone tests ended in a very dense, granular layer beneath the clayey units, approximately 6 m below the river water level.

Three boreholes were drilled to verify the lateral variability of the sensitivity of the clay layers along the anticipated retrogression axis: the first at the edge of the slope (27062), the second where the inhabited area begins (27063), and a third near the end of the zone, where the new residential development was planned (27064). However, the liquidity index and remoulded shear strength data (measured using the Swedish cone) show that the clay deposit does not have the properties necessary at the site of the second borehole (27063 in Figure 3) for a flowslide or a spread to occur there. The other boreholes laterally adjacent to this one (27066 and 26067) also supported this observation, leading to the conclusion that neither a flowslide nor a spread could reach the inhabited area. However, as the clay at the edge of the slope is prone to severe retrogressive landslides, an area was retained near the Sainte-Anne River, the dimensions of which were estimated based on the 1897 spread and on an average of the scars left by previous landslides on the *Noire* River, which flows parallel to the Sainte-Anne River, a little less than 2 km to the northwest (Figure 2).

The results of these investigations ultimately allowed the new residential development to proceed safely and confirmed that the existing residential area was not actually exposed to the danger of HRL. The zoning could therefore be reduced, while maintaining a safety margin along the banks of the Sainte-Anne River.

Finally, it should be noted that during the investigation, the riverbanks were monitored by drone and trail camera to ensure the safety of the village residents until the study was completed.

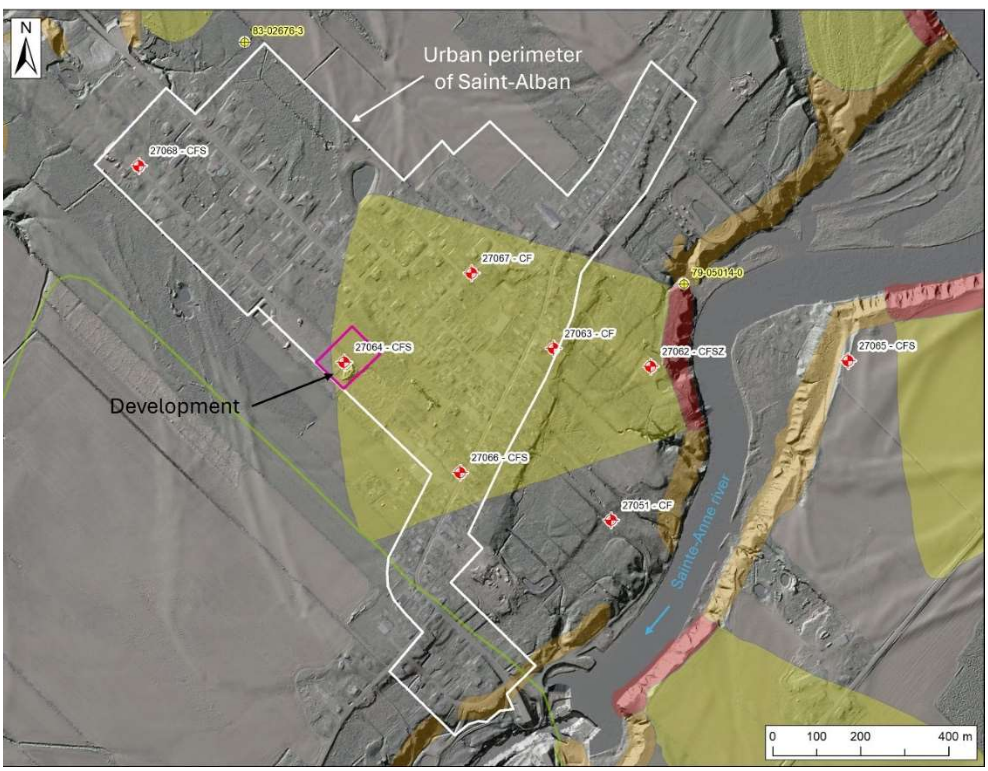


Figure 1 : View of the entire site, the area mapped in the 1980s, and the location of boreholes and soundings. The yellow areas indicate those identified as having the potential for highly retrogressive landslides.

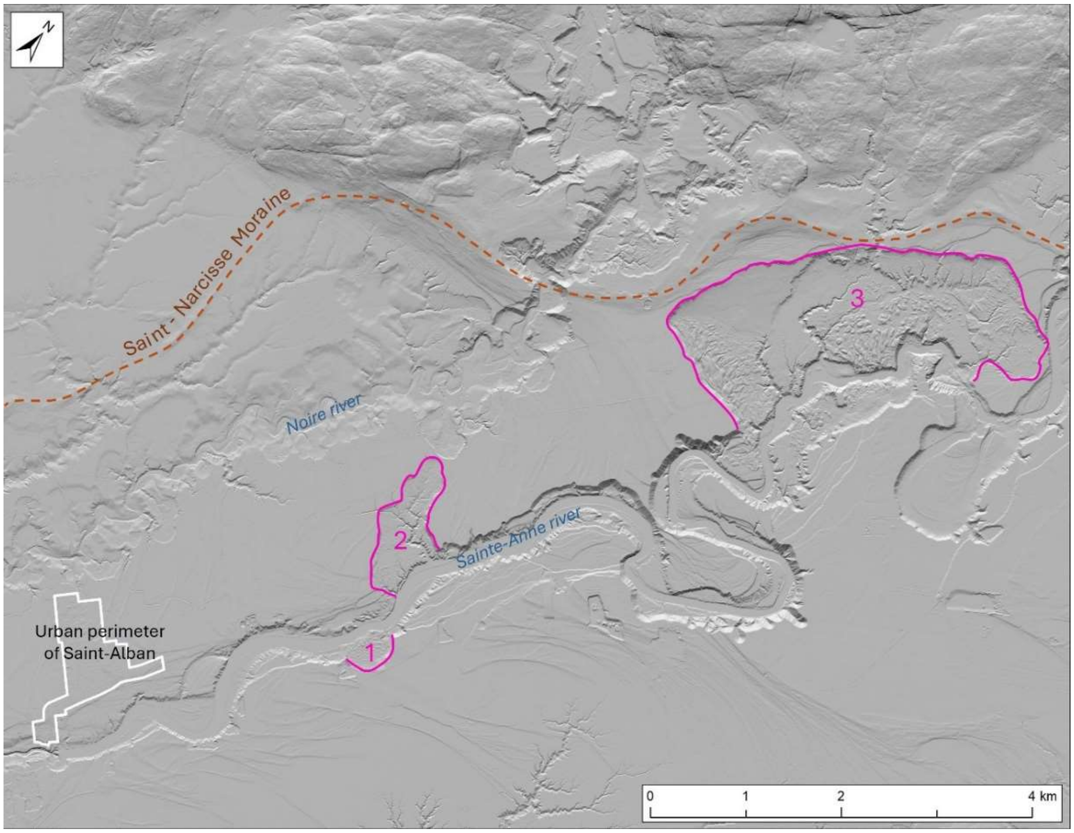


Figure 2 : Location of the three highly retrogressive landslide scars upstream of the study site (pink lines) and the Noire River to the northwest. Note the position of the Saint-Narcisse moraine axis, which partially runs along the Sainte-Anne River and then the Noire River.

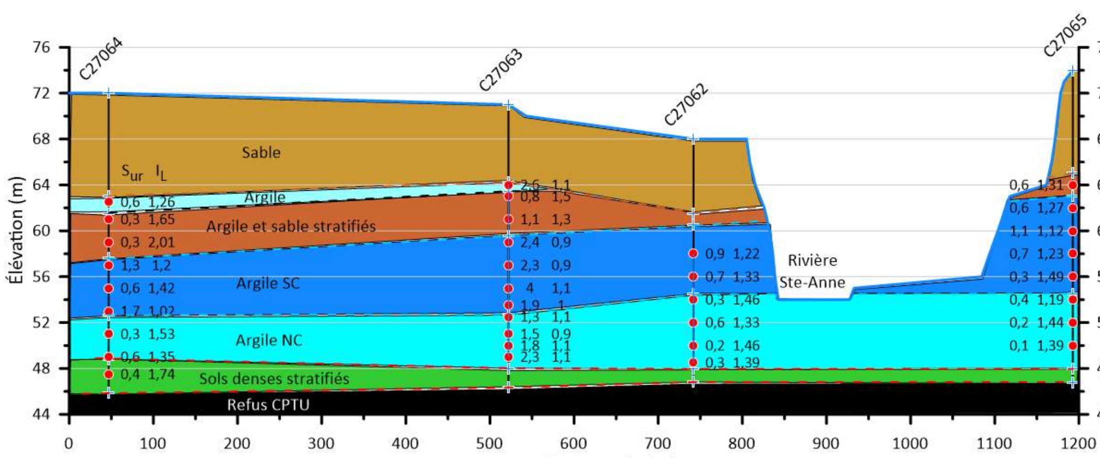


***Figure 3** : Longitudinal stratigraphic section of the study area, along the axis of boreholes 27062 to 27065. Note: the figure shows a very high vertical exaggeration (13.6 times) in order to better visualize the soil layers and laboratory data. Note: Bathymetry below the river water level is not shown because it is not known with precision.*

INFOCLIP 3 : Emergency situation following a deep rotational landslide in April 2022, *Noire* River, Saint-Alban

Context

On April 13, 2022, a deep rotational landslide occurred on the right bank of the *Noire* River in Saint-Alban, just next to where Saint-Philippe Road crosses the river (Figure 1). This river is well known for the numerous scars left by highly retrogressive landslides along its course, which have left very characteristic and easily recognizable shapes on aerial photographs (Figure 2). The area has been cited for this reason in numerous bibliographical references, notably by Karrow (1972) and Mollard & Janes (1985), for its characteristic "thumbprint" shapes, typical of spreads (Therrien et al., 2025).

At the site of the 2022 landslide, the river forms a pronounced meander that erodes the foot of the slope, which has a total height of approximately 17 m (Figure 3). Before the landslide occurred, the slope had an inclination of just under 40° over a height of almost 10 m at its base (Figure 4). A farm field is located at the top of the slope, and the Saint-Philippe Road bridge is just downstream. The numerous scars of highly retrogressive landslides visible on the digital terrain model in this area (Figure 1) revealed that the clayey soils in this region are susceptible to remoulding. A survey conducted by the Ministry of Natural Resources in 1983, located 250 m north of the study site, confirmed the presence of this type of clay. A subsequent borehole drilled closer to the site (Figure 5) showed that the clay deposit between depths of 3.5 and 27 m had liquidity index between 1.2 and 3.2 and sensitivities ranging from 200 to 550 at depths greater than 9 m. The undrained shear strength, measured with a Nilcon scissometer in intact condition, varies between 33 and 68 kPa.

The landslide that occurred on April 13, 2022, was 41 m wide and carried away a strip of land measuring 16 to 18 m at the top of the slope (Figures 4 and 6). The backscarp of the landslide was very steep, rising 11 m in height. The configuration of the slide indicated that the rupture surface was deep and extended below the river level. There was little debris from the slide at the foot of the escarpment, but it did obstruct the opposite bank of the river, directing water toward the foot of the slide (Figure 6).

The factors that contributed to triggering the landslide were increased pore pressure following spring snowmelt and rainfall in previous weeks, as well as severe erosion at the base of the slope located on the outer bend of a meander in the *Noire* River (Figure 3). Considering the very unfavorable geometry left by the landslide, as well as the presence of sensitive clay and the history of highly retrogressive landslides in this area, the danger that the geometry of the backscarp would lead to the development of a larger landslide was strongly anticipated. Since the bridge and Saint-Philippe Road were located a short distance from the landslide (Figure 6), they were considered to be under imminent threat from its possible expansion.

A 200-meter safety perimeter closing off the road and bridge was then recommended by the MTMD, and a detour was put in place pending the completion of work to counter the development of a highly retrogressive landslide. The work was carried out in two phases: the first, in May 2022, was an emergency measure to temporarily secure the site and reopen the road; the second, in February 2024, was to protect the slope from erosion and ensure the long-term safety of the site.

Preliminary work (emergency phase)

To eliminate the possibility of the landslide expanding in the short term, it was decided to quickly gentle the slope of the landslide scar. The main challenge was to ensure worker safety. An access route was therefore established from a safe distance behind the site, following an area lower than the adjacent plateau (Figure 7), resulting in a height below the critical level for the development of highly retrogressive landslide (Leroueil et al., 2025). This safe access allowed to start excavation of the adjacent plateau to ensure that it was no longer high enough for a potential retrogressive process to continue, based on the criteria defined by Locat (2022, 2023):

- $\gamma H/S_{uv} < 24I_P$

The excavation area therefore progressed from the rear toward the landslide scar (Figure 7). The access road then approached the landslide's side scarp on the northeast side, where the slope was less steep, to begin sloping the landslide's escarpments (Figure 7).

These preliminary works were completed by dumping rocks along the bank of the river to prevent erosion from attacking the base of the landslide, and near the bridge to protect its piers (Figure 8), taking care not to cause any narrowing of the river. In the following weeks, the municipality dug a channel through the debris in the river to reduce erosion, since the design and obtaining of all the permits for the final phase of the work, to ensure the site's sustainability, required several months. The site was monitored using a trail camera installed on the opposite bank to ensure that the preliminary work did not deteriorate.

Final work

The final work, carried out approximately a year and a half later, consisted mainly of installing permanent riprap at the base of the slope to provide lasting protection against erosion by the river, as well as redeveloping the entire site (Figure 9). The riverbed was repositioned to its original location when the riprap was put in place.

Site characteristics

One of the distinctive features of the site was the presence of a system of very deep subvertical cracks, observed in the backscarp of the landslide scar (Figure 10) during the first field visit following the event. With the loss of ground at the top of the slope estimated at between 16 and 18 m, these cracks were therefore located at a considerable distance from the initial edge of the slope. Such subvertical fissure systems were also observed in the scarps of the recent, highly retrogressive landslides at Saint-Thuribe and Sainte-Monique (sites 1 and 4 of this tour), more than a hundred meters from the initial crest of the slopes. The question of their origin and development will be addressed at the first stop, at the Saint-Thuribe site.

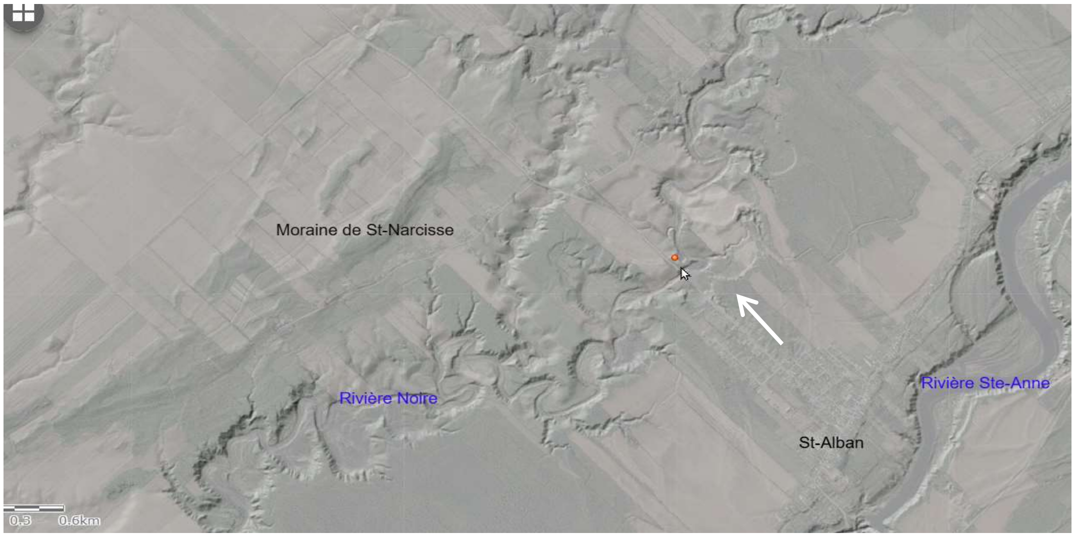


Figure 1 : General location and site of the 2022 landslide along the Noire River (where the white arrow points).

Figure 2 : Aerial photo from 1955 showing typical patterns of highly retrogressive landslides along the Noire River. The arrow points to the site of the 2022 landslide. (Source: photo A-14602-98 – Energy, Mines and Resources – Canada)

Figure 3 : Helicopter view in 2017 showing the presence of an erosion notch at the foot of the slope. (Source: MTMD – DGG)

Figure 4 : Topographic section at the site of the 2022 landslide.

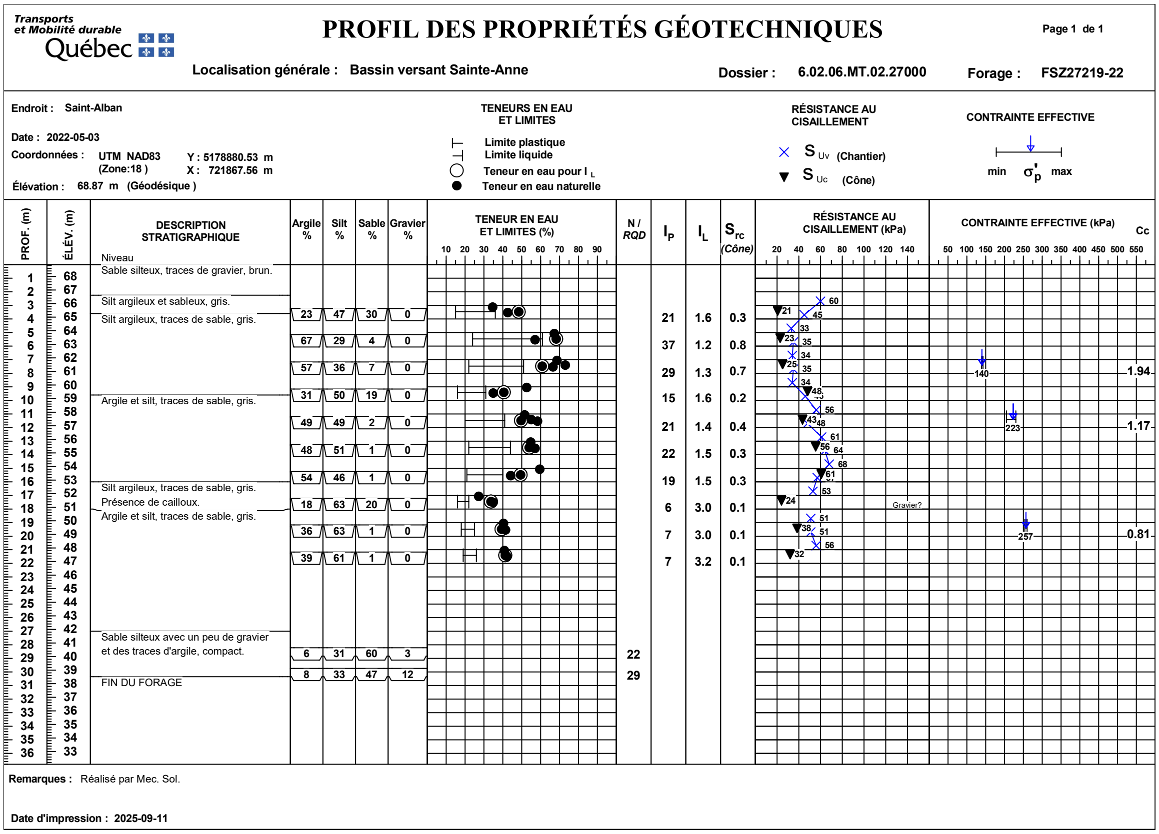


Figure 5 : Geotechnical profile of borehole FSZ27219-22, drilled near the site.

Figure 6 : Drone view of the April 2022 landslide along the Noire River, near the road and bridge on Saint-Philippe Road. (Source: MTMD – DGG)

Figure 7 : Excavation of ground levels gradually approaching the landslide scar. The access road was placed in a location where it was lower than the adjacent intact plateau. (Source: MTMD – DGG)

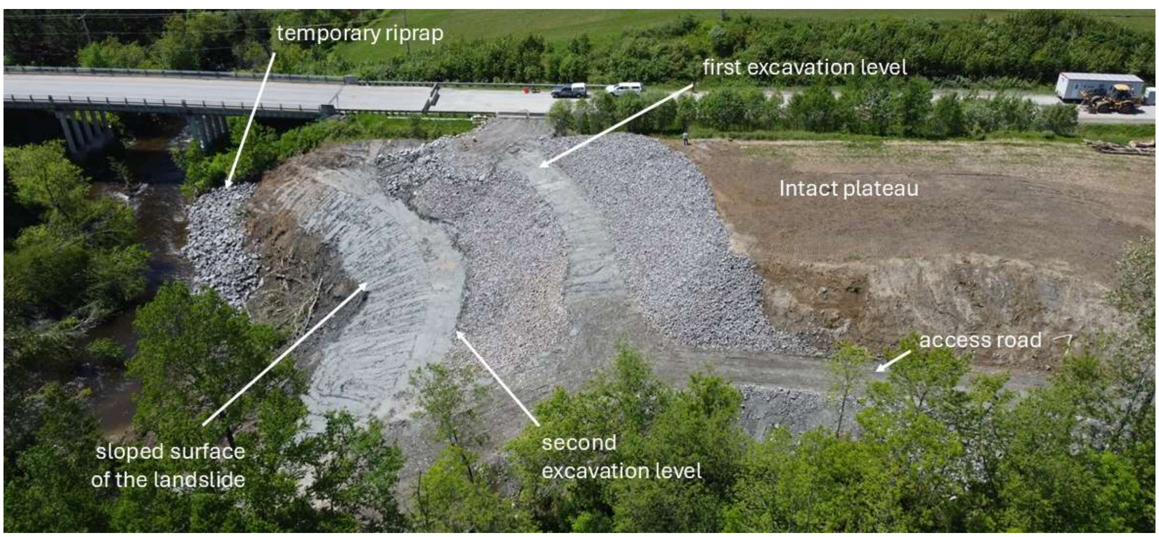


Figure 8 : View of the preliminary phase completed. (Source: MTMD – DGG)


Figure 9 : View of the final works. (Source : MTMD – DGG)


Figure 10 : View of the backscarp of the landslide, showing a well-developed system of very deep subvertical cracks.

INFOCLIP 4 : Sainte-Anne-de-la-Pérade experimental site

Introduction

Before reaching the second stop, our drive will take us close to the Sainte-Anne-de-la-Pérade experimental site (Figure 1). At this location, Laval University and the Quebec Government (MTMD) have equipped the site with instruments to monitor various aspects of groundwater conditions, which are a fundamental element of any slope stability study in clayey soils.

The site has been the subject of numerous surveys and boreholes to characterize the site (Figure 1), whose stratigraphy is relatively more complex than the models often used in slope stability studies in sensitive clays in Quebec (Lefebvre, 1986, 2017). In addition, a multitude of instruments have been installed, and measurements have been monitored over many years and are still ongoing. Several piezometer arrays (standard electrical and hydraulic) have been installed to monitor piezometric conditions over time (Germain et al., 2020). Different piezometer installation methods have also been tested to verify their performance (Young et al., 2022). In addition to an existing government weather station nearby, another has been installed directly on site to measure precipitation, barometric pressure, solar radiation, wind direction and speed, snow depth, air temperature, and humidity on an hourly basis.

In addition, probes were installed in the unsaturated zone next to the local weather station to monitor water infiltration and soil temperature. Thermistors, water content probes, and tensiometers were used to monitor infiltration between 2.5 cm and 2 m deep.

Geological conditions

The Quaternary stratigraphy at this site is relatively complex, as frequently found in post-glacial marine clay slopes in Quebec, where highly draining units alternate with uniform, highly impermeable units and, finally, interbedded layers (Figure 2).

Main findings

The results indicate that the local groundwater and pore pressure dynamics cannot be explained using simplified conceptual models of the site. A more detailed analysis indicates that groundwater dynamics and pore pressures in the massive clay deposits on site are determined by (i) the highly heterogeneous nature of the local geological materials (ii) the contrasting hydraulic and geotechnical properties of these materials, (iii) the presence of two unconfined aquifers on site, one at the surface and the other at depth, and (iv) the presence of the Sainte-Anne River. These results were used to create a new conceptual model that illustrates the complex groundwater flow system present at the site (Figures 2 and 3) and shows the importance of including the hydrogeological context in slope stability analysis.

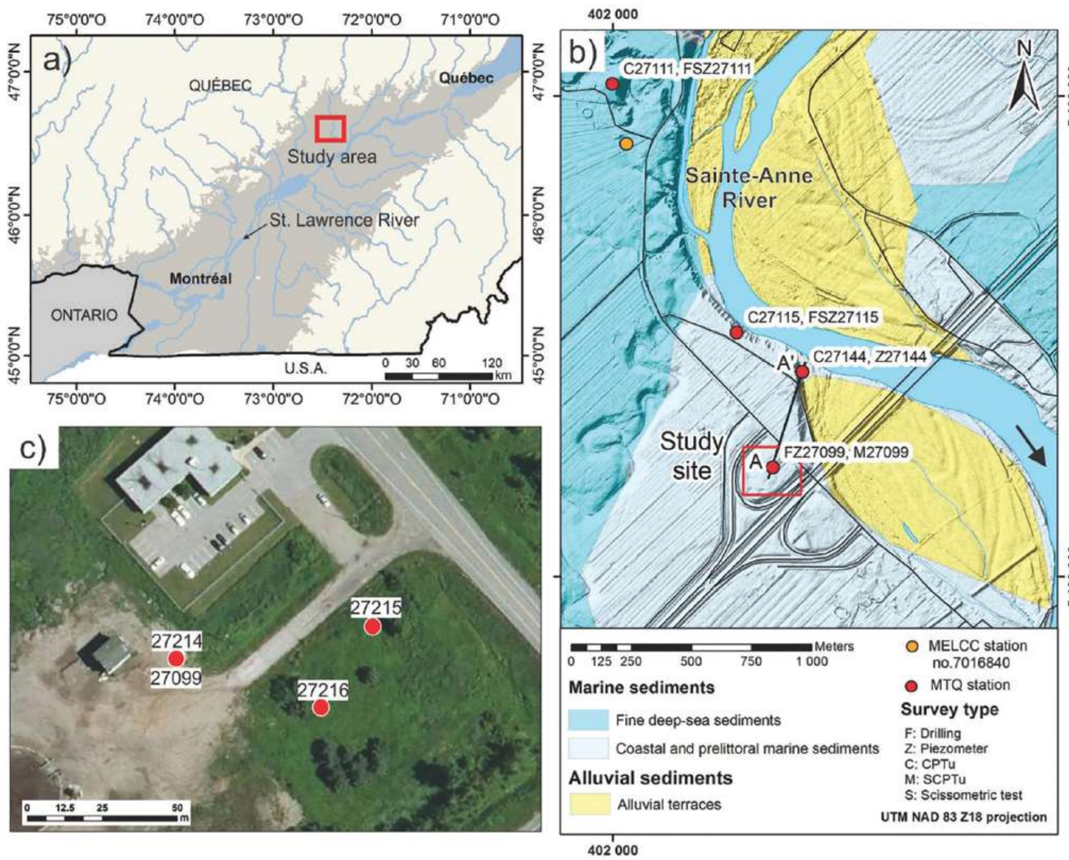


Figure 1 : Site location. (Taken from Germain et al., 2020)

The following methods were used to install electric vibrating wire piezometers (Young et al. 2022):

- single piezometers in sand packs (SP);
- multi-level piezometers in sand packs (MLSP);
- multi-level piezometers fully grouted with bentonite (FGB)
- multi-level piezometers fully grouted with cement-bentonite (FGCB).

Based on monitoring that lasted approximately two years, it was found that SP, MLSP, and FGB piezometers provided the most reliable results, as piezometers installed at the same depth using these methods recorded similar pressure variations consistent with the hydrogeological context. Of the two installations completely sealed with cement-bentonite grout, one collapsed completely due to a hydraulic short circuit, probably caused by preferential flow along the wires of the embedded instruments. The lack of a standard method for mixing cement-bentonite grout at the time of construction likely contributed to the failure of the BGCF installations, as the grout mixture used in this study was probably too viscous to provide adequate sealing.

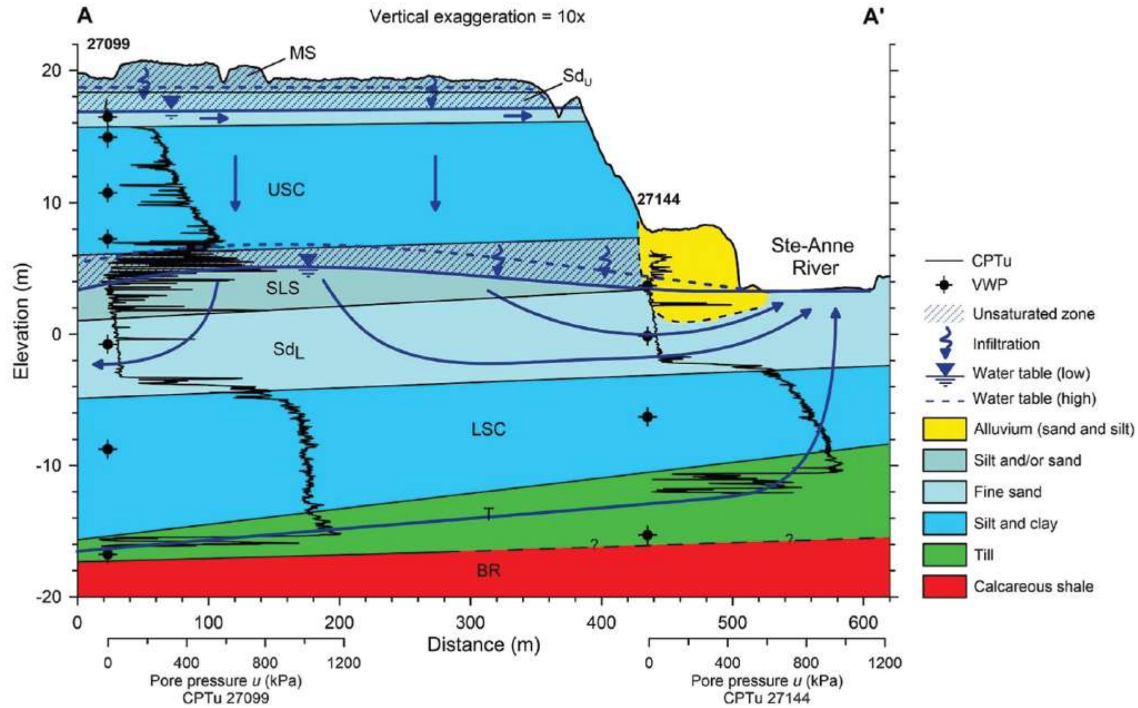


Figure 2 : Stratigraphic section of the site and conceptual model of groundwater flow at the Sainte-Anne-de-la-Pérade site, along profile A-A' shown in Figure 1. Two pore pressure profiles obtained from piezocone testing are included in the profile. (Taken from Germain et al., 2020)

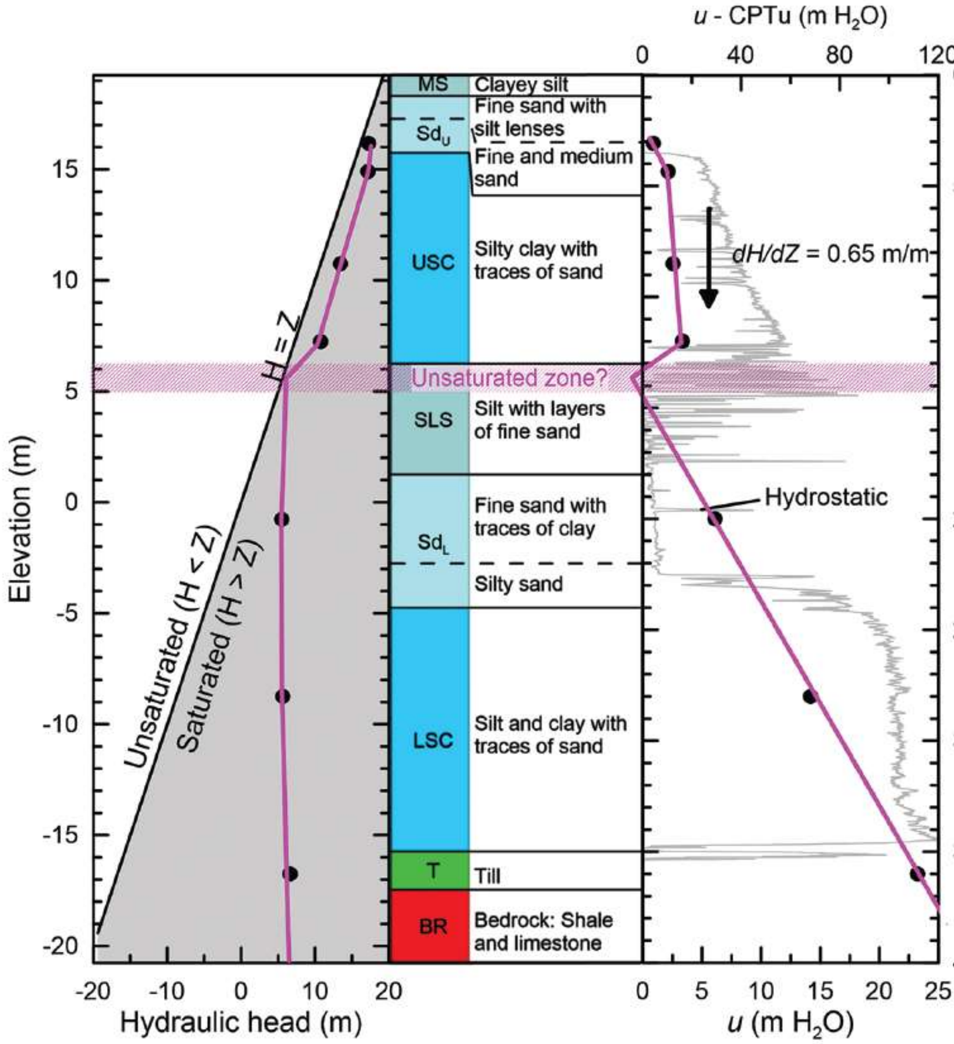


Figure 3 : Hydraulic gradient profiles, stratigraphy, and dynamic values of pore pressure as a function of depth. The black dots represent measurement points. The purple line shows two different flow regimes present at the site: downward flow exists in the upper 14 m of the section, while flow is largely hydrostatic at depths of 15 m and below. H: hydraulic head; Z: elevation. (Taken from Germain et al., 2020)

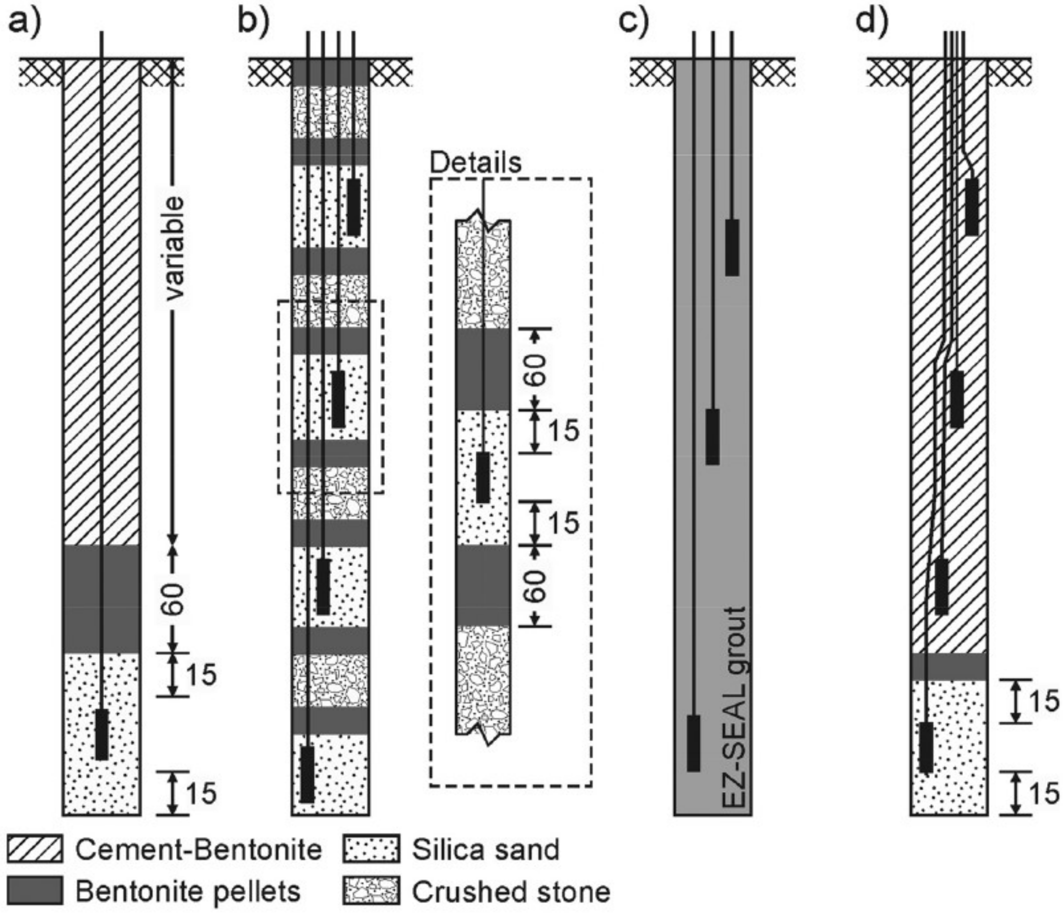


Figure 4 : Diagram (a) of a single piezometer installed in a sand pack (SP), (b) of a multi-level piezometer array where each piezometer is installed in a sand pack (MLSP), (c) a piezometer nest fully cemented in a single borehole using a grout composed exclusively of bentonite (FGB), and (d) a piezometer nest composed of a cement-bentonite mixture in a single borehole (FGCB). Length is expressed in cm. (Taken from Young et al., 2022)

INFOCLIP 5: The Laviolette Bridge over the Saint Lawrence River

General Information

The first two stops of the technical visit took place on the north shore of the Saint Lawrence River. To reach the final two sites, located on the south shore, we will cross over at the Laviolette Bridge, just upstream from downtown Trois-Rivières (Figure 1). The bridge is named after the historical figure credited with founding the city.

The Saint Lawrence is one of the most significant rivers in North America. Stretching 1,197 km, it connects the Great Lakes to the Atlantic Ocean and serves as a major gateway into the North American continent. Its average flow is estimated at 16,800 m^3/s, compared to about 18,000 m^3/s for the Mississippi River. It was through this waterway that ocean waters penetrated deep inland to form the post-glacial seas of southern Quebec and southeastern Ontario: the Goldthwait Sea to the east, the Champlain Sea upstream of Quebec City, and the Laflamme Sea in the Saguenay–Lac Saint-Jean area.

Between Montreal to the west and Quebec City, to the east, the river is generally between 1 and 4.7 km wide, except in its central portion where it widens up to nearly 14 km to form Saint-Pierre Lake over a 25 km stretch. Downstream from Quebec City, the river becomes an estuary, widening rapidly to between 14 and 48 km. Near the Gaspé Peninsula, approximately 650 km east of Quebec City, it widens sharply again, reaching between 100 and 115 km before opening into the Gulf of Saint Lawrence.

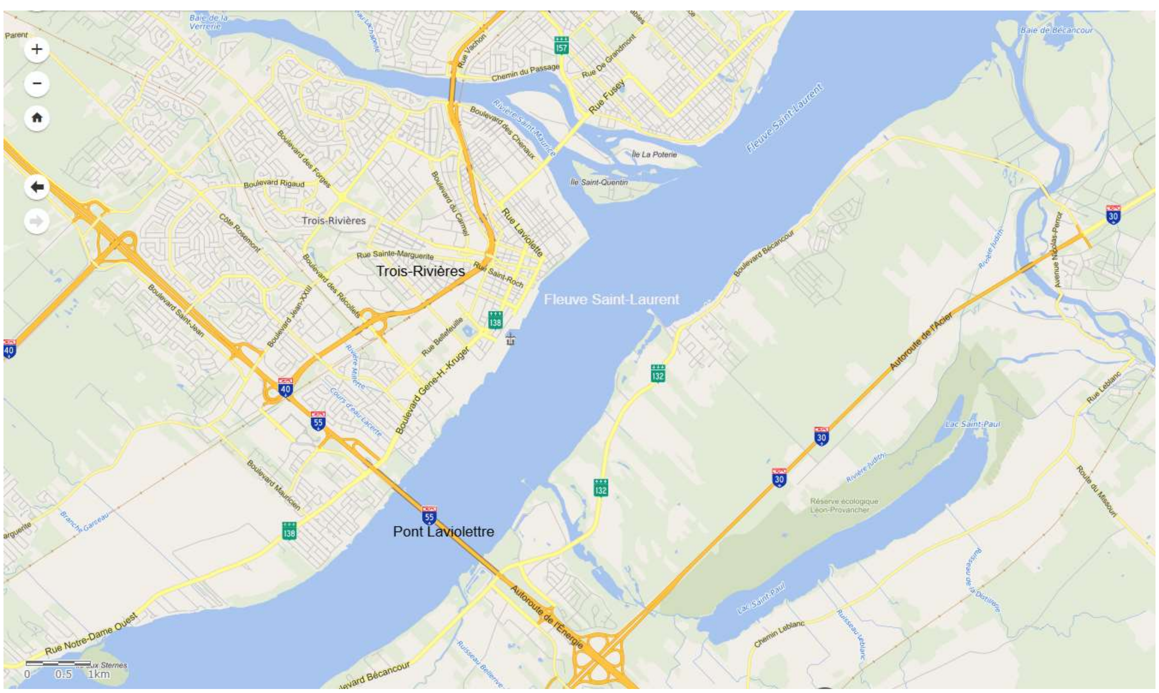
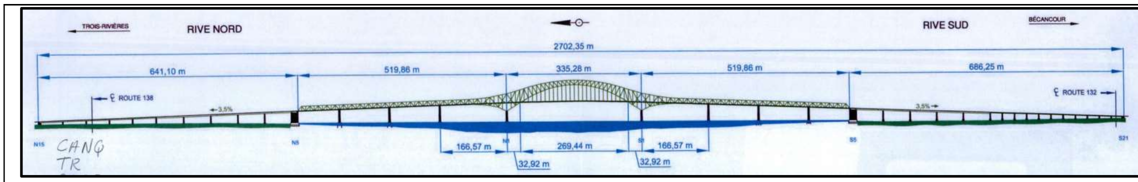


Figure 1: Location of the Laviolette Bridge.

While there are some ferry connections between the riverbanks from Quebec City to Montreal, the Laviolette Bridge is the only road link between these two major economic hubs, which are about 270 km apart. Located nearly halfway between them, the bridge plays a strategic role in ensuring the smooth flow of road traffic within the Saint Lawrence Valley—the most densely populated region in the province of Quebec (home to over 85% of the province's population).

At the site of the Laviolette Bridge, the river is approximately 1.7 km wide. The bridge spans a total length of 2,707 m, with a central span of 335 m, and rises to a height of 106 m above the river to accommodate cargo ships traveling the Saint Lawrence Seaway (Figure 2A). Its elongated shape with a highly arched central span resembles a caterpillar in motion (Figure 2B).



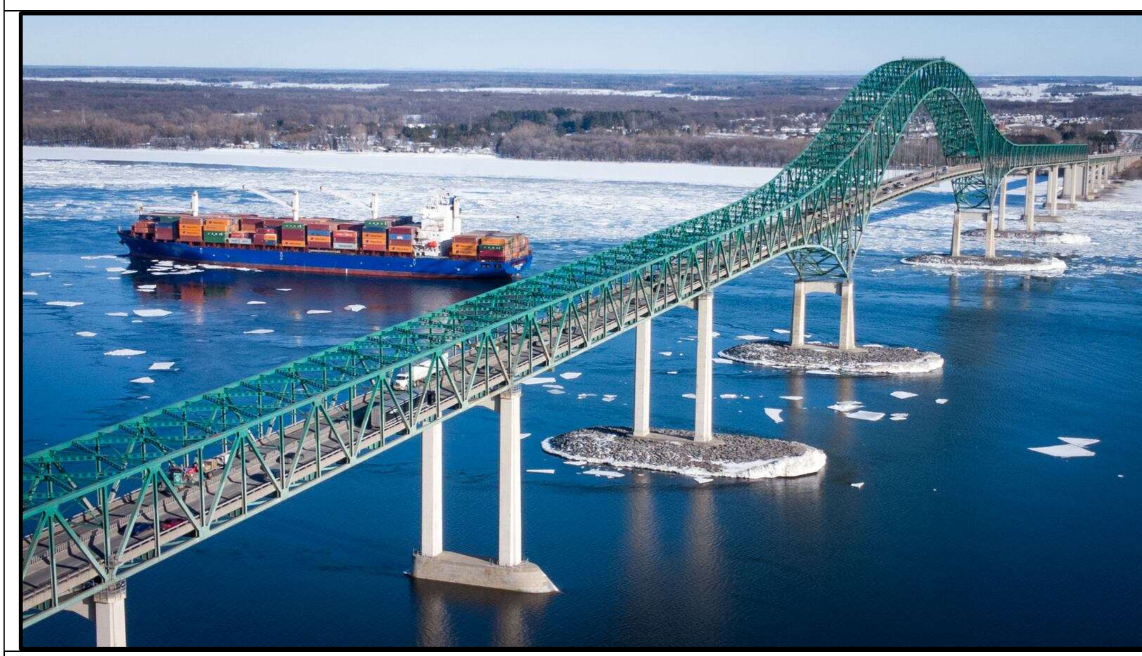


Figure 2: A (top): sketch of the bridge structure. B (bottom): photo of the bridge showing the four central piers protected by riprap to guard against ship collisions.

Statistical Information and historical aspect

Key facts about this major structure:

- Construction began: May 15, 1964
- Official opening: December 20, 1967
- Length: 2,707 m
- Height: 106 m
- Width: 16.7 m
- Traffic:
    - Initial: 12,000 vehicles per day
    - 2004: 31,000 vehicles per day
    - 2017: 39,000 vehicles per day
    - 2023: 42,000 vehicles per day
- Major maintenance and repair projects:
    - 1988: Installation of protection around bridge piers
    - 2006–2007: Replacement of the north and south approach slabs
    - 2023–2025: Replacement of the central deck slab

Historical Aspects

After many years of political pressure from the local population, construction of the Laviolette Bridge finally began on May 15, 1964. Construction lasted three years and was completed on December 20, 1967. However, a tragic accident occurred on September 7, 1965, when a crack at the base of a construction caisson led to its collapse and to an explosion. Twelve workers lost their lives, six others were injured, and a diver also died during the body recovery operations.

The bridge cost a total of $50 million at the time, the equivalent of $454 million in 2025. Its steel structure is the longest in Quebec at 1,375 m. Highway 55, which runs across the bridge, also serves as a north-south axis through the St. Lawrence Lowlands and connects highway 20 and highway 40, two of Quebec major highways running east-west along the river. Originally handling 12,000 vehicles daily, traffic had risen to 42,000 vehicles per day by 2023, underscoring the bridge's strategic importance to a region with significant industrial hubs.

Many will recall the serious maritime accident in 2024 in the Port of Baltimore, USA, where a cargo ship lost propulsion and maneuverability due to an electrical failure. The vessel drifted and struck a pier of the Francis Scott Key Bridge, a structure comparable to the Laviolette Bridge (Figure 3A). The impact destroyed the right-bank pier, causing the bridge deck to collapse, followed soon after by the left-bank section—resulting in the complete destruction of the bridge (Figure 3B).

A similar incident occurred at the Skyway Bridge in Florida in 1980, prompting the Canadian Coast Guard to assess the vulnerability of Canadian bridges to such impacts. A 1982 report identified the Laviolette Bridge as Canada's most vulnerable bridge to maritime collisions. The piers were deemed too narrow. The Quebec Ministry of Transportation therefore launched studies to address this risk, considering the heavy maritime traffic (cargo ships, bulk carriers, container ships, oil tankers) and the difficult navigation conditions of the Saint Lawrence, which is considered one of the most complex inland waterways in the world (Corporation of Central Saint Lawrence Pilots, website consulted in September 2025).

Figure 3: A (top): The Francis Scott Key Bridge in Baltimore before the 2024 disaster.
B (bottom): Bridge collapse after cargo ship impact in 2024. Photos: Wikipedia.

Protection of the Laviolette Bridge Piers

To protect the Laviolette Bridge piers—passed by thousands of ships every year—stone islands were constructed around the four central piers (Figure 2B). The Danish Hydraulic Institute was consulted for the design of these structures. The sizing of the islands was particularly influenced by the potential penetration of an unladen ship (a situation where the bow is raised relative to the stern, which, combined with a low draft, increases penetration risk).

The construction of these protection structures posed major challenges, due to both the depth of water and the presence of sensitive, compressible clay soils in the riverbed. As shown in Figure 4, the post-glacial marine clay layer ranges between 17 and 25 m thick at the site of the four stone islands.

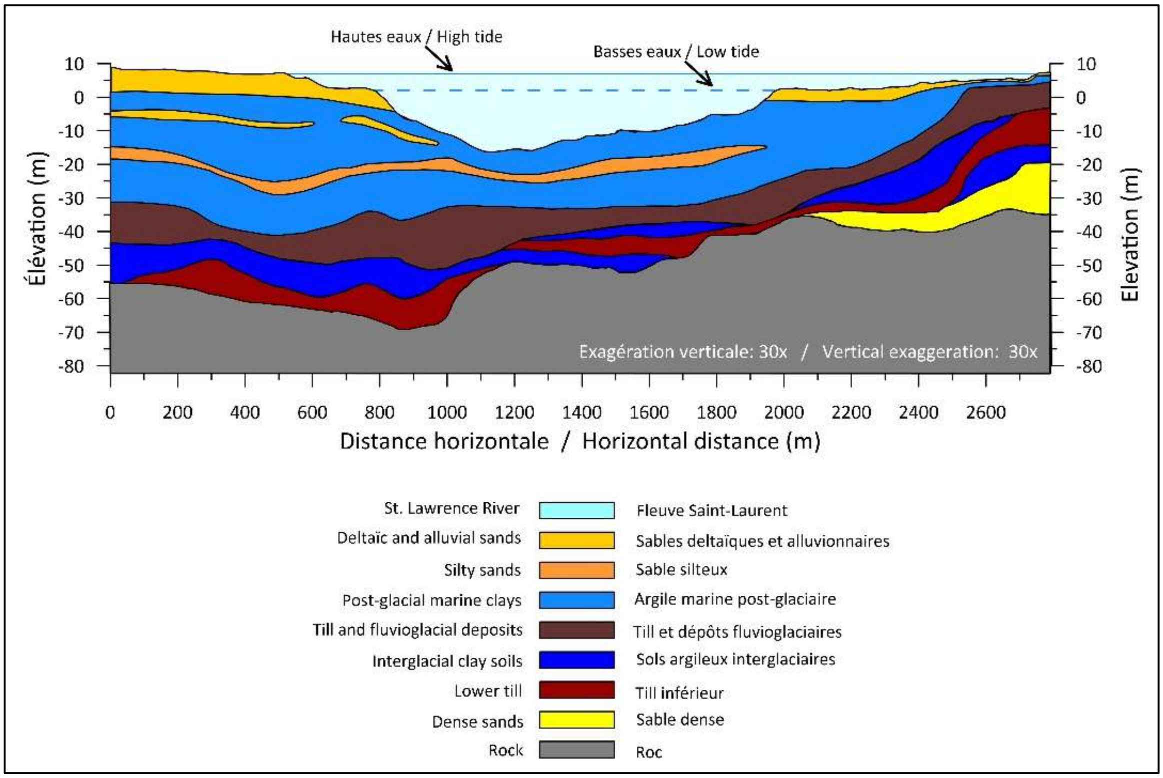


Figure 4: Simplified stratigraphic cross-section across the Saint Lawrence River along the Laviolette Bridge (source: Geo.Demers, 1963).

From a geotechnical perspective, three key aspects were analyzed:

- Settlement of foundation soils around the piers, estimated at between 30 and 230 mm depending on the pier;
- Additional loads transmitted to the pier caissons by the fill, which could be supported by the existing foundations but still caused about 10 mm of additional settlement;
- Stability of the foundation soil under the weight of the rock fill, which was ensured using slopes of 1.5H:1V down to -4 m, and 2.0H:1V from -4 m to the top at +4 m.

To protect against ice forces, a special rock armor layer using 1.5-ton blocks was placed above -4 m, and the upper fill platform was raised to +5 m.

Other significant challenges included evaluating the impact on hydraulic flow, navigation, and ice movement in the spring, and especially the construction and control of these massive rock embankments at depths reaching 15 to 20 m.

Construction was completed in 1988, and four years later, the structure was put to the test when a vessel with a rudder failure struck the rock shield but caused no damage to the bridge.

A 2023 bathymetric survey, conducted 35 years after the construction of the stone islands, reveals their full extent around the protected piers compared to the unprotected adjacent piers (Figure 5). Downstream sedimentation since their installation is also visible.

Finally, major refurbishment work was carried out in 2006–2007 to replace the approach slabs and from 2023 to 2025 to replace the central deck slab.

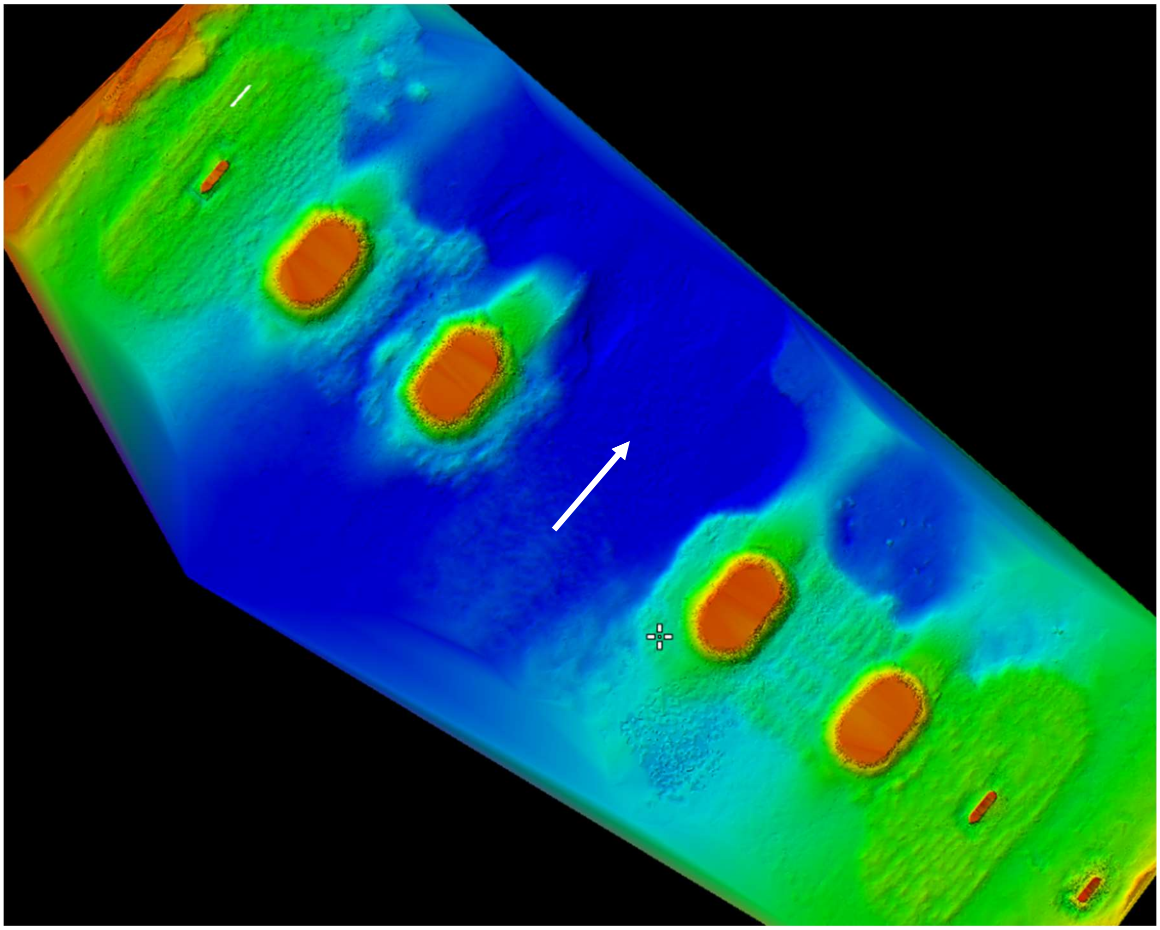


Figure 5: 2023 bathymetric survey showing the extent of the four protective islands and adjacent unprotected piers of the Laviolette Bridge. Flow direction is indicated by the white arrow. North is at the top.