An earthflow in sensitive Champlain Sea sediments at Lemieux, Ontario, June 20, 1993, and its impact on the South Nation River[1]

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A large (est. volume 2.8×10^6 m^3) landslide occurred in sensitive Leda clay on the east bank of the South Nation River at Lemieux, Ontario (45.4°N, 75.06°W), on June 20, 1993. The earthflow involved an area of about 17 ha and retrogressed a total of 680 m, 555 m into the flat plain above the river. No lives were lost but a motorist was injured when he drove into the landslide crater. The 1993 landslide occurred 4.5 km downstream of the well-known 1971 South Nation River landslide along a stretch of river that had experienced other historical landslides in 1895 and 1910. A band of earlier, undated, retrogressive sliding, between 100–130 m in width, was present at the base of the slope that failed in 1993, and the earthflow was probably triggered by a reactivation of these failures. Borehole information obtained in 1986 and 1987 in the vicinity of the landslide indicates that a zone of soft, sensitive marine clay existed beneath the flat farmland, which was overlain by a stiffer cap consisting of laminated marine–estuarine sands and deltaic silts and sands. The morphology of the debris suggests a mechanism that involves the fluidization of much of the landslide mass and subsidence, translation, and rotation of cap blocks. The stability number for the site was approximately 9.6, suggesting that the flow could have occurred as a result of extrusion of the soft sensitive clay layer due to undrained cap loading. Landslide debris temporarily blocked the South Nation River, causing flooding upstream and adversely affecting water quality downstream.

Key words: landslide, earthflow, sensitive clay, debris hazards, water quality.

Un important glissement de terrain (volume estimé de 2,8 M m^3) eut lieu le 20 juin 1993 dans un dépôt d'argile sensible Leda situé sur la rive est de la rivière South Nation à Lemieux, Ontario (45,4°N; 75,06°O). Le glissement couvrait une aire d'environ 17 ha et a rétrogressé sur une distance de 680 m, dont 555 m dans le terrain plat adjacent à la rive. Aucune perte de vie n'a été déplorée mais un automobiliste fut blessé lorsque son véhicule tomba dans le cratère. Le glissement de 1993 eut lieu 4,5 km en aval du glissement bien connu de la rivière South Nation de 1971 qui s'est développé dans une zone qui avait déjà subit d'autres glissements importants en 1895 et 1910. Des signes d'un ancien glissement de type rétrogressif et de date inconnue ont été observés sur une largeur d'environ 100–130 m à la base du glissement de 1993. On peut supposer que ce dernier fut déclenché par une réactivation de ces surfaces de rupture. Des sondages effectués en 1986 et 1987 à proximité du glissement indiquent qu'une zone d'argile marine sensible et molle est située sous une couche plus raide de sables stratifiés d'origine marine–estuaire et de limons et sables deltaïques. La morphologie des débris suggère un mécanisme de rupture caractérisé par la liquéfaction de presque la totalité de la masse du glissement et par le tassement, translation et rotation des blocs de la couche raide. La valeur approximative du facteur de stabilité de 9,6 suggère que l'écoulement aurait pu se produire à la suite de l'extrusion de la couche d'argile sensible et molle résultant d'un chargement non drainé de la couche raide. Les débris du glissement ont bloqué temporairement la rivière South Nation provoquant des inondations à l'amont et détériorant la qualité de l'eau à l'aval.

Mots clés : glissement, coulée de boue, argile sensible, risques de glissement, qualité de l'eau.

[Traduit par la rédaction]

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Introduction

Beginning at approximately 15:30 on 20 June, 1993, a large landslide (Fig. 1), hereafter referred to as the Lemieux landslide, occurred in sensitive Champlain Sea sediments on the east bank of the South Nation River, 0.5 km north of the former townsite of Lemieux, Ontario, 50 km east of Ottawa at 45.4°N, 75.06°W (Fig. 2). The landslide occurred 4.5 km downstream of the well-known 1971 South Nation River landslide (Eden et al. 1971; Mitchell 1978*a*, 1978*b*; Mitchell and Markell 1974) (Figs. 2 and 3). The landslide severed County Road 16. A man was injured when he drove his pickup truck into the crater formed by the landslide, and was later rescued by a Canadian Forces helicopter. The statements of eyewitnesses summarized in Brooks et al. (1994) indicate that the major movements of the landslide lasted about an hour and had ceased by about 16:30.

The landslide involved land that had been zoned as high landslide hazard by local authorities and had been purchased by the South Nation River Conservation Authority as part of its landslide hazard mitigation program. As part of the same program, the nearby village of Lemieux had been dismantled in 1989–1990. Some of the farm buildings which existed at the site prior to the buyout would have been involved in the landslide.

The debris dammed the South Nation River, causing flooding upstream. In addition, when the river overtopped the debris dam 3 days later, it adversely affected water quality for agricultural and domestic use downstream. Trees washed out of the debris were also a hazard to boaters along both the South Nation and Ottawa rivers.

Preliminary estimates by the South Nation River Conservation Authority of the indirect (the buyout of 28 homes prior to the landslide) and direct (immediate postslide costs and cost of river cleanup) costs associated with the Lemieux landslide are Cdn. $2.5 million.

This report is a preliminary description of the landslide and its effect on the South Nation River based on ground and aerial reconnaissance undertaken between June 21 and July 7,

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FIG. 1. Aerial view of the 1993 Lemieux landslide which took place on June 20, 1993. View is toward the southwest looking up the South Nation River. Severed County Road 16 is seen at bottom left and County Road 8 bridge discussed in text is seen upstream of the landslide in the middle distance. Note impoundment of river and upstream flooding. Photo taken on June 23, 1993.

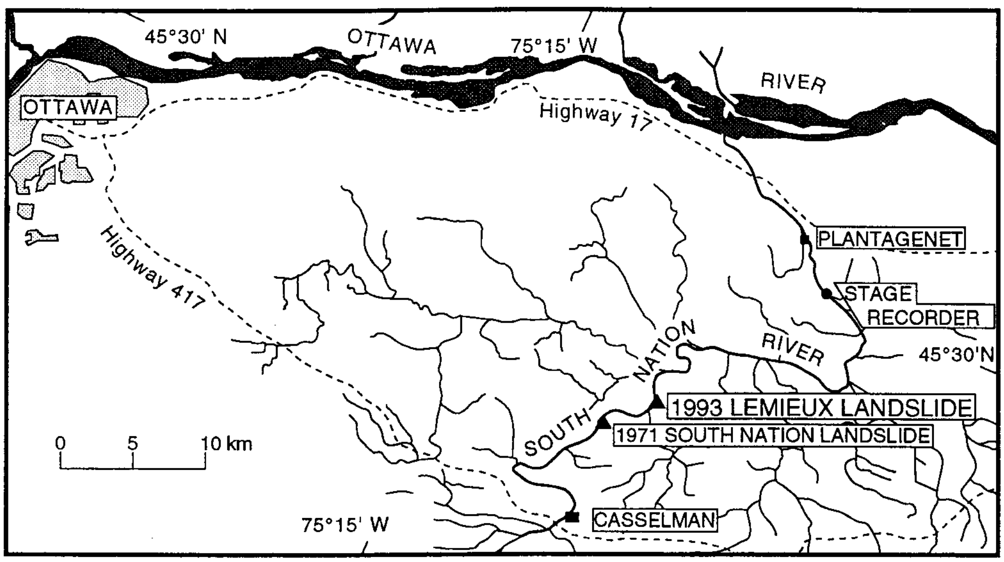

FIG. 2. Location map of the South Nation River and Lemieux landslide.

an examination of hydrographic and climatic records, and geotechnical reports prepared in the late 1980s for the South Nation River Conservation Authority. No detailed postslide geotechnical investigation has been carried out to date, but an illustrated photographic documentation of the event has been prepared (Brooks et al. 1994).

Terminology

Landslides in sensitive clays are generally complex events (e.g., Mitchell and Markell 1974; Carson 1977; Mitchell 1978*a*, 1978*b*). In the Varnes (1978) classification, the Lemieux landslide is classified as a very rapid earthflow or a quick-clay flow involving the lateral spreading and (or) liquefaction of a subjacent layer and the subsequent liquefaction and (or) disintegration of all or part of the entire slide mass. Retrogressive rotational sliding may also be involved in the early and later stages of the movement. In addition, simple translation may occur which may be accompanied by rotational sliding (e.g., Odenstad 1951). In describing the landslide, the morphological terminology of Mitchell (1978*b*, Fig. 22) is followed.

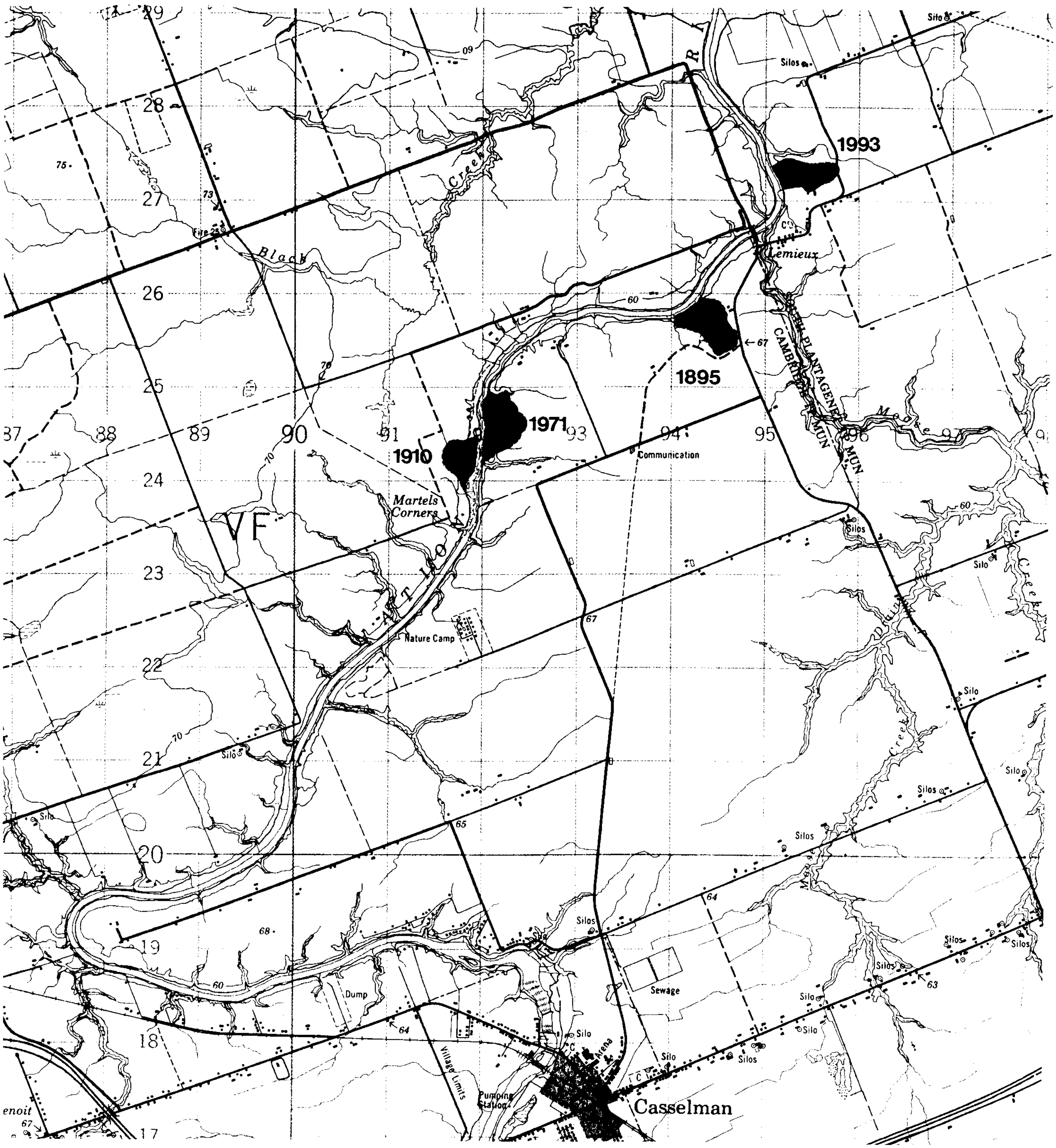

FIG. 3. Map of the South Nation River in the vicinity of Lemieux, Ontario, showing location of Lemieux landslide and historical sensitive-clay flows (based on National Topographic System map sheet number 31 G/6© Her Majesty the Queen in Right of Canada with permission of Natural Resources Canada). Grid line spacing is 1 km.

Geologic background

The landslide occurred in an area of the Ottawa Valley known as the Russell and Prescott sand plains (Chapman and Putnam 1984), a broad expanse of featureless rural landscape (cf. Fig. 1). The sand plains have a level surface at about 70 m asl with the maximum relief of about 23 m in the river valleys that cross them.

The sand plains are the remnants of an estuarine-deltaic complex formed during deglaciation and dissected during subsequent emergence by the developing Ottawa River. The dissection resulted in braided channels being established at about 10 000 BP (Gadd 1976; Richard 1982). The islands between the channels preserve the coarser late emergence sediments, forming a cap of sands that overlie marine silts and clays. During dissection, marine clay was exposed on braided-channel margins and huge landslides later took place (Gadd 1976; Richard 1982). Holocene erosion by rivers cutting across the plains and by gullies cutting back into the valley sides has also exposed the marine clay at depth and led to landsliding, although on a much smaller scale.

The South Nation River cuts across one of the remnant islands between Casselman and about 1.5 km downstream from Lemieux, where the river emerges onto a broad, flat, clay plain. Within this 20-km reach of valley, the South Nation River is single-channelled and is generally confined by the valley sides. Several fragmentary terrace surfaces are present along the valley sides; there is almost a complete absence of flood-plain development. Proximal to the 1993 landslide, the preslide width of the river channel averages about 50 m, measured from NTS map 31 G/6. The channel gradient through the valley is not known, but is probably very low, since the average river slope over the lower 100 km of the river basin is only 0.02% (Chapman and Putnam 1984).

In the area of the Lemieux landslide, the river occupies a narrow valley incised up to 23 m into the surrounding flat sand plain. Valley-side slopes unaffected by retrogressive sliding or quick-clay flows are in the order of 16–20°.

River incision has exposed marine clay along the valley sides of the South Nation River (Richard 1982) beneath the cap of sand, creating conditions very favourable for clay flows. Clay flow scars are common on both sides of the river (Richard 1982) and display acute retrogressional behaviour, with maximum retrogression distances into the sand plain being in the range 650–700 m for a riverbank height of 23 m (Fig. 3). In this 20 km stretch of river, at least 13 landslide scars can be identified on air photographs (Brooks et al. 1994). Included in this number are retrogressive slide complexes, involving limited retrogression of up to 130 m.

The 1993 clay flow took place along a part of the South Nation River that has experienced significant historical landslide activity. In addition to the 1971 landslide mentioned above, major landslides are also known to have occurred in 1895 and 1910 within 4.6 km of the 1993 landslide (Fig. 2) (Mitchell 1978*b*).

The 1993 landslide source area

In plan (Figs. 4 and 5), the crater of the 1993 landslide is elongate with a length:width (L:W) ratio of 2.7 and is about 10–12 m in depth at present. Although an unknown thickness of debris covers the floor of the crater, the spoil is at least 12 m deep in the South Nation River channel immediately below the scar. In the absence of postlandslide borings the depth of the failure can only be estimated. From field evidence and information from borings summarized below, the minimum average depth is estimated to be 18 m, varying from 23 m depth at the river to about 13 m at the head of the crater. The maximum retrogressive distance from the South Nation River is 680 m and 555 m from the headscarp of the previous retrogressive sliding. The mouth of the crater is not of the bottleneck type, although there is a slight narrowing of the neck at the river (Figs. 1 and 5). The margins of the slide appear to have been constrained by gullies.

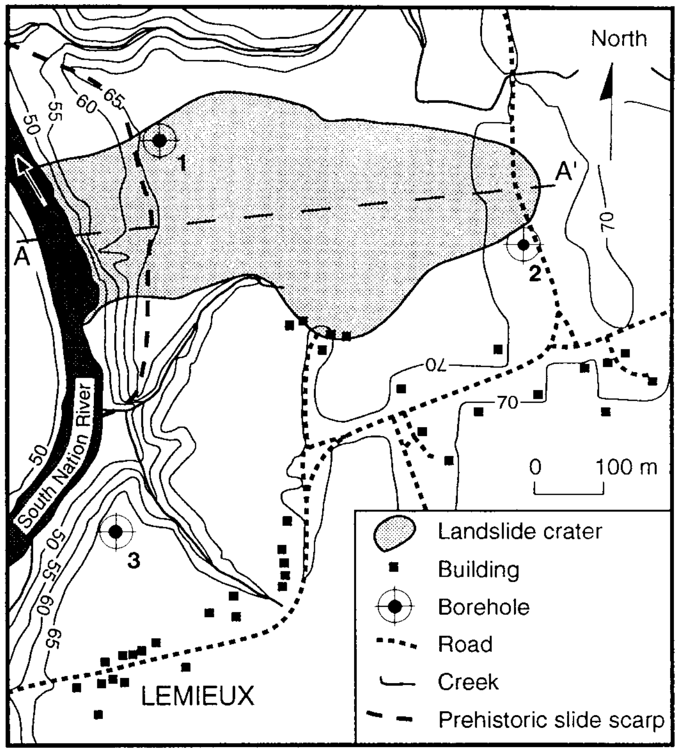

FIG. 4. Map showing the extent of the 1993 Lemieux earthflow, area of prelandslide retrogressive sliding adjacent to the South Nation River channel, and locations of boreholes drilled in the late 1980s. A–A′ is line of section in Fig. 8. Map shows the location of buildings before 1989–1990 buyout. Contour interval is 5 m. Modified from Province of Ontario 1 : 10 000 map 10-18-4950-50250.

Large-scale pre- and post-slide topographic maps are not available at present, but a minimum volume estimate has been made based on the outline of the landslide crater in Fig. 4 and the minimum average depth noted above. The landslide covers an area of 17 ha, 14 ha of which is flat farmland. The volume of displaced material beneath the flat farmland (assuming a mean thickness of 18 m) is therefore about 2.5×10^6 m^3; the volume in the valley-side slope is about 0.3×10^6 m^3 yielding a total of about 2.8×10^6 m^3, which is within the volume range of $2.5–3.5 \times 10^6$ m^3 estimated by Brooks et al. (1994).

About 1.5×10^6 m^3 of the debris evacuated the crater and flowed into the South Nation River (Fig. 5).

Within the crater, grounded, prismatic-shaped blocks are found in a mass of remoulded spoil at various locations (Figs. 6 and 7) including near the crater mouth. Within these blocks, laminations are horizontal, or near horizontal, in attitude. In addition, in the areas of the debris nearest the crater margin, contiguous sharp-crested ridges, about 3 m in height and consisting of blue-grey laminated silts and sands, parallel the sides of the crater (Figs. 5 and 6). As in the case of the individual blocks the laminations exposed in these ridges are invariably horizontal, or near horizontal, in attitude and the fact that the sediments are lower than their original position in the crater side indicates that translation has been accompanied by some subsidence. Rafts of sod are also present in the crater (Fig. 5), some with trees still standing upright in their growing position. Rotated blocks are also evident in the debris, particularly around the margins of

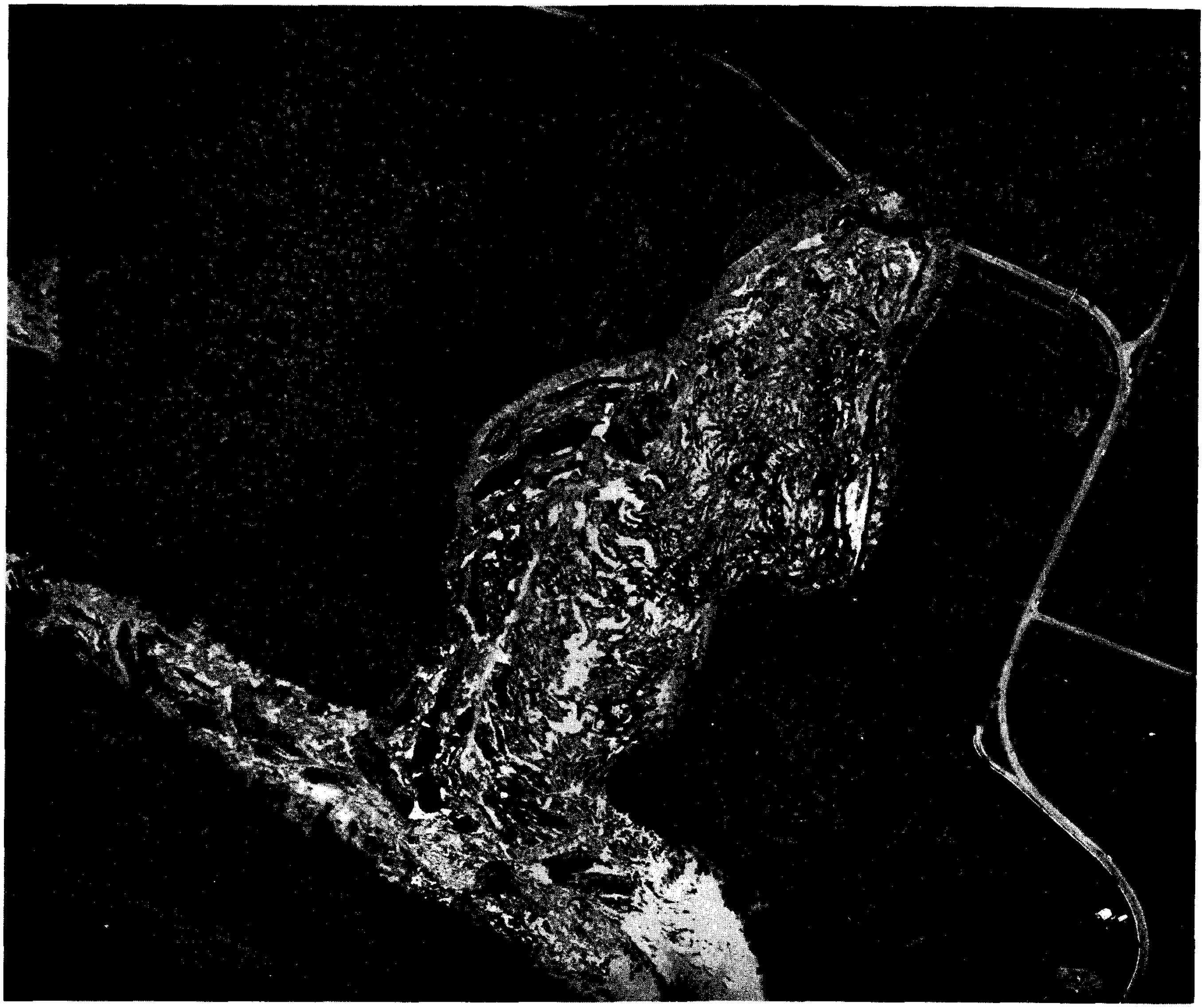

FIG. 5. Vertical aerial photograph of the 1993 Lemieux landslide taken on June 22, 1993 (courtesy of South Nation River Conservation Authority). Direction of flow of South Nation River is shown by arrows. Scale is approximate.

the crater (Fig. 6). They are also found in the vicinity of the prismatic blocks, where they have appeared not only to have rotated and sunk into the remoulded spoil, but have been subject to disintegration by sliding along laminations in response to the rotation (Fig. 7).

The morphology of the debris is therefore consistent with a mechanism that involves the break up of a stiffer cap and the subsidence and transport of the cap blocks in a mass of remoulded spoil, much of which flowed out of the crater into the valley of the South Nation River.

Stratigraphic and geotechnical data

Stratigraphic and geotechnical data for the landslide site are available from the three boreholes (located in Fig. 4), which had been drilled in 1986 by the Ontario Ministry of Natural Resources (borehole 2) and in 1987 by Golder Associates (boreholes 1 and 3). In broad outline the stratigraphy of the site consists of three units (Fig. 8; Table 1) that coarsen upward, consistent with emergent conditions at the time of deposition, and thin toward the head of the landslide crater. The units are as follows:

(1) An upper cap of loose brown silty sand (3–7 m in thickness; depth range 0–7 m).

(2) A middle unit of grey-blue laminated interbedded silts and sands (5–10 m in thickness; depth range 3–17 m); the grounded blocks that litter the floor of the crater and the sharp-crested ridges referred to above are made up of this unit. In borehole 1, strength decreases with depth within the unit as reflected in a decrease in standard penetration resistance. At the base of this unit the plastic limit W_p = 25%, liquid limit W_L = 52.5%, liquidity index I_L = 0.4.

(3) A lower unit of marine clay, below 8–17 m depth. In borehole 1, the auger rods descended under their own weight (without the weight of the hammer) below 17 m ; W_p varies from 19.9 to 27.8%, and W_L varies from 31.4 to 56.2%. Below 19 m, natural moisture contents exceed the liquid limit and in this zone the liquidity index is 1.6 at 19.8 m, 1.4 at 23 m, and 1.6 at 24.8 m. Field vane tests indicate natural values of undrained shear strength C_u between

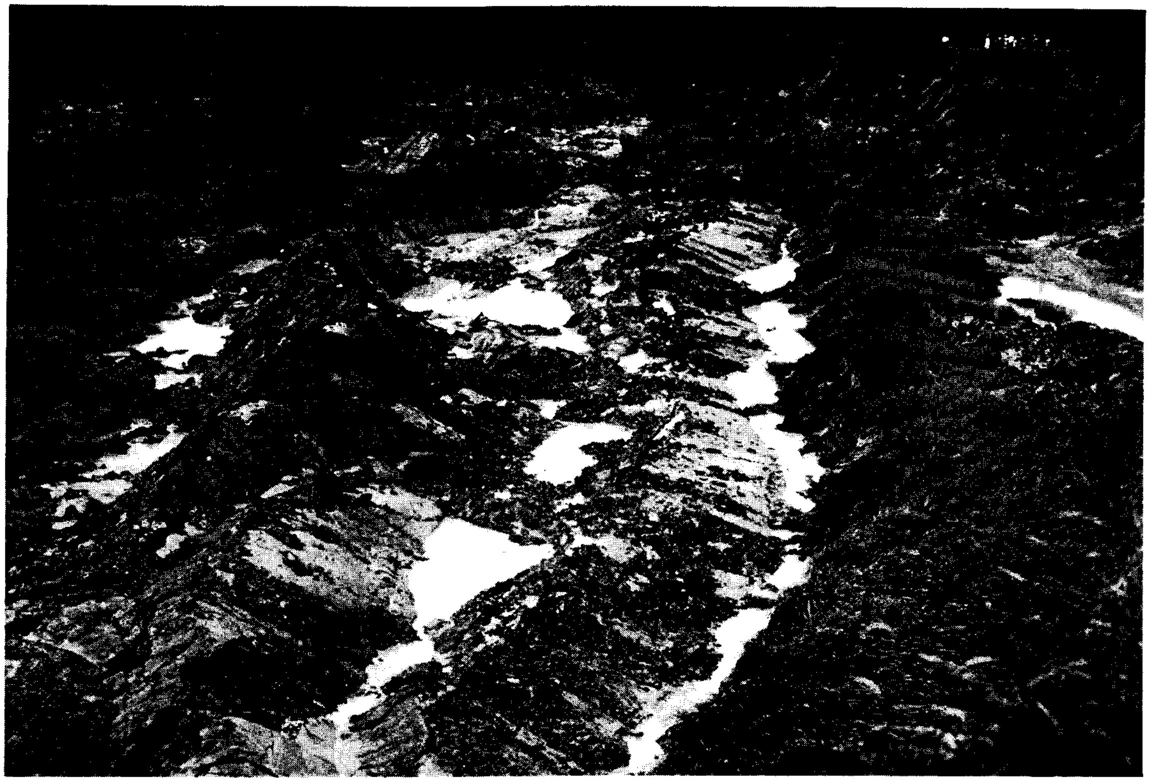

FIG. 6. The Lemieux landslide crater on June 21, 1993, about 24 h after the landslide took place. View is to the east along the south rim where onlookers (top right) provide scale. Note (from right to left) rotational blocks below the scarp, an exposed sliding surface within displaced blocks which formed along rotated lamination surfaces, clay ridges about 3 m in height, and sod from former field surface, and another clay ridge. Laminations in the clay ridges are horizontal.

41 and 76 kPa. In the zone between 18 and 23 m, the range of C_u is 41–53 kPa, with an average of 47 kPa. Below 17 m remoulded C_u values are generally less than 10 kPa (Fig. 8), yielding a range of sensitivities between 4.3 and 11.4.

Data on salt concentration from borehole 3 indicate a concentration of Na, K, Ca, and Mg of 0.5 g/L in unit 3.

Piezometric data from borehole 1 (Fig. 8) suggest the presence of several perched water tables within the sequence.

Subsurface stratigraphical and geotechnical data (Fig. 8; Table 1), therefore, indicate the presence of a lower unit of soft marine clay overlain by a stronger, stiffer cap consisting of the grey-blue laminated interbedded sands and silts and the overlying brown silty sand. In the middle to lower part of the marine clay unit, values of I_L in excess of 1 indicate that the unit is very sensitive to remoulding. Field vane tests measured high sensitivities (>4) in the upper part of the unit at a location that corresponds to the base of the landslide. This evidence suggests that the Lemieux landslide occurred as a result of strength loss in a sensitive clay zone located between 8 and 23 m beneath the surface and that the liquefaction of most of the slide mass beneath the stiffer cap was due to its high liquidity index ($I_L > 1$).

Pre-1993 landslide conditions

A band of inactive retrogressive sliding, about 100–130 m in width, formed the valley side at the location of the landslide (Fig. 4) (Richard 1982). A partial cross section through the slide complex is now exposed in the north wall of the crater mouth. The 1993 landslide was probably triggered by a reactivation of these failures, although it is not clear why the initial retrogressive sliding did not trigger the quick clay flow that eventually took place in 1993. A gully was also present upslope of the retrogressive slide complex (Fig. 4). Erosion in this gully may have locally destabilized the slope, leading to the larger scale failure.

Landslide debris

Upon failure, the landslide debris, consisting of liquefied silts and clays, intact silt and sand blocks, and rafts of sod, some with trees still upright in their growing position, flowed directly into the bottom of the South Nation valley (Figs. 5 and 9), then spread laterally in both the upstream and downstream directions. The upstream arm of the flow travelled underneath the County Road 8 bridge situated about 800 m from the landslide source area (Fig. 10). No damage occurred to the bridge, as there was sufficient clearance to allow the debris to pass safely underneath, although upright trees being carried in the flow struck the span. When it finally came to rest, the landslide debris covered about 3.3 km of the valley bottom up to 12 m in depth, extending approximately 1.6 km upstream and 1.7 km downstream of the flow crater.

From aerial photography taken on June 22, the landslide deposit ranges in width from 120 to 160 m in the area immediately opposite the crater mouth (Fig. 5). This width occurs because the debris crossed the valley bottom and buried a terrace along the opposite side of the valley. Towards the downstream end, the deposit narrows to about 50 m where it is confined entirely within the South Nation River channel

A

B

FIG. 7. (A) View to the west toward the mouth of the crater of debris and intact blocks. Scarp at left is approximately 9 m high. Arrowed pyramidal block is that shown in (B) (photograph courtesy of J.M. Aylsworth, taken on September 21 1993, 3 months after the landslide). (B) Grounded prismatic blocks, rotated blocks, and remoulded spoil in the centre of the crater. Pyramidal block to right of person is that arrowed in (A). View is toward the north rim. Photograph taken July 7, 1993.

(Fig. 9). At the time of the photography, the upstream extension of the debris was inundated with impounded river waters (Fig. 5).

The rate of flow of the debris along the valley bottom is not known, but must have been rapid; fishermen standing near the County Road 8 bridge are reported to have run for their lives to avoid an "8 ft high wall of water" (Ottawa Citizen, June 21, 1993). This wave was probably generated by the displacement of river water by the landslide debris as it travelled upstream. The downstream extension of the debris also created a displacement wave as the Water Survey of Canada stage recorder located near Plantagenet Springs (28.4 km downstream) shows an abrupt rise in stage at 17:20 on June 20, about 110 min after the beginning of the landslide (Fig. 11).

Impact upon South Nation River

Impoundment of the river

Spread over about 3.3 km, the landslide debris forms a long, relatively narrow debris dam in the bottom of the South Nation valley. The dam obstructed the flow of the South Nation River, causing the impoundment of river waters. Beginning immediately after the landslide, water levels rose gradually over several days, eventually to a level about

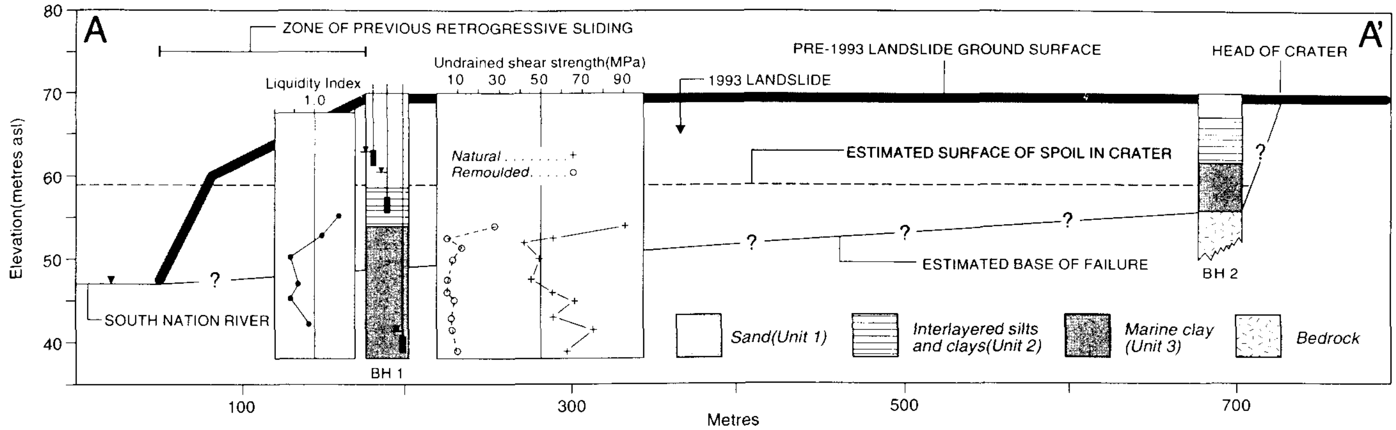

FIG. 8. Approximate cross section (A–A′ in Fig. 4) and geotechnical profile of Lemieux landslide based on drilling carried out in 1986 and 1987. Vertical exaggeration is five times horizontal. Boreholes (BH) projected onto cross section. Data in borehole 1 provided by Golder Associates.

TABLE 1. Lemieux landslide: summary of geotechnical data

Unit	Lithology	Depth range (m)	Index properties W_p (%)	W_L (%)	W (%)	I_L	Undrained strength C_u (MPa)[a] Natural	Remoulded	Sensitivity
1	Silty fine sand	0–7	—	—	—	—	—	—	—
2	Interlayered silty clay	3–17	25	52.5	36.7	0.4	68.7–91.7	23.8–28	2.19–3.18
3	Silty clay	8–32	19.9–27.8	31.4–56.2	36.4–59	0.8–1.6	41.7–76.7	3.7–10.9	4.3–11.4

[a]Field vane tests.

12 m above the preslide riverbed in the area of the County Road 8 bridge, a level controlled by the elevation of deposits opposite the mouth of the landslide crater. The impoundment extended about 18 km upstream to the base of the rapids at Casselman, flooding at least one home in the valley. It also backflooded the lower reaches of adjoining tributary streams.

The impounded waters initially overtopped the crest of the landslide dam late in the evening of Tuesday, June 22, and by late morning Wednesday June 23 a strong current was flowing over the debris. Erosion into the landslide deposits by the restored flow lowered the impoundment 20–30 cm by midafternoon Thursday, June 24, 1993, and a further 1.2 m by early afternoon Saturday, June 26, 1993. Inspection of the valley opposite the crater mouth on July 7 revealed the river flowing within a sinuous channel 4 m wide entrenched about 2 m into the landslide debris. River incision into the landslide dam is anticipated to proceed relatively slowly because of the low height to width ratio (1:300) of the landslide deposit, the general cohesiveness of the clays and silts forming the intact rafted blocks, and the abundant trees and strips of sod forming the surface of the landslide deposit. The risk of an outburst flood is therefore believed to be low.

In the early afternoon of Wednesday June 23, 1993, flow over the landslide debris was observed as a broad, shallow sheet extending entirely across the debris in the valley bottom. Rafted blocks of silt and clay, clumps of trees, and strips of sod protruded through the flow forming small islands. The turbidity of the river water changed relatively abruptly from dark brown to light grey, beginning opposite the mouth of the landslide scar.

Effect upon the downstream flow of South Nation River

The impoundment of the South Nation River by the landslide debris is apparent in the discharge record at the Plantagenet Springs station (Fig. 11), but the flow was not affected severely. Over the course of Sunday, June 20, 1993, the river stage had been falling gently (Fig. 11). At the time of the landslide (15:30) the stage was 0.868 m, equivalent to a discharge of about 22.4 m^3/s (Fig. 11). At 17:20, the stage rose abruptly by 0.082 m. As noted above this is believed to represent a wave of water displaced downstream by the landslide as it surged along the South Nation valley bottom.

Immediately after the rise, the stage fell by about 0.028 m, then continued to decrease more slowly, attaining its prewave level at 19:40. The 2.33 h period between the rise and fall stage reflects the very slight gradient of the river channel (D. Rowe, personal communication, 30 June 1993) and severe dampening of the wave by the channel bottom over the 28.4 km distance from the landslide to the stage recorder.

From 19:40 to 01:00 on June 21, the river stage continued to fall, eventually reaching 0.787 m (or a discharge of 11.9 m^3/s), reflecting the impoundment of the river by the landslide. After 01:00 on June 21 the flow increased in response to heavy precipitation falling within the watershed (Fig. 11).

As noted above, the South Nation River began to overtop the landslide dam late Tuesday, June 22, but an obvious response to this additional flow is apparent only after 12:30 Wednesday, June 23, when discharge again began to rise.

Turbidity

The possible impact of the landslide upon turbidity levels caused concern to farmers and communities downstream

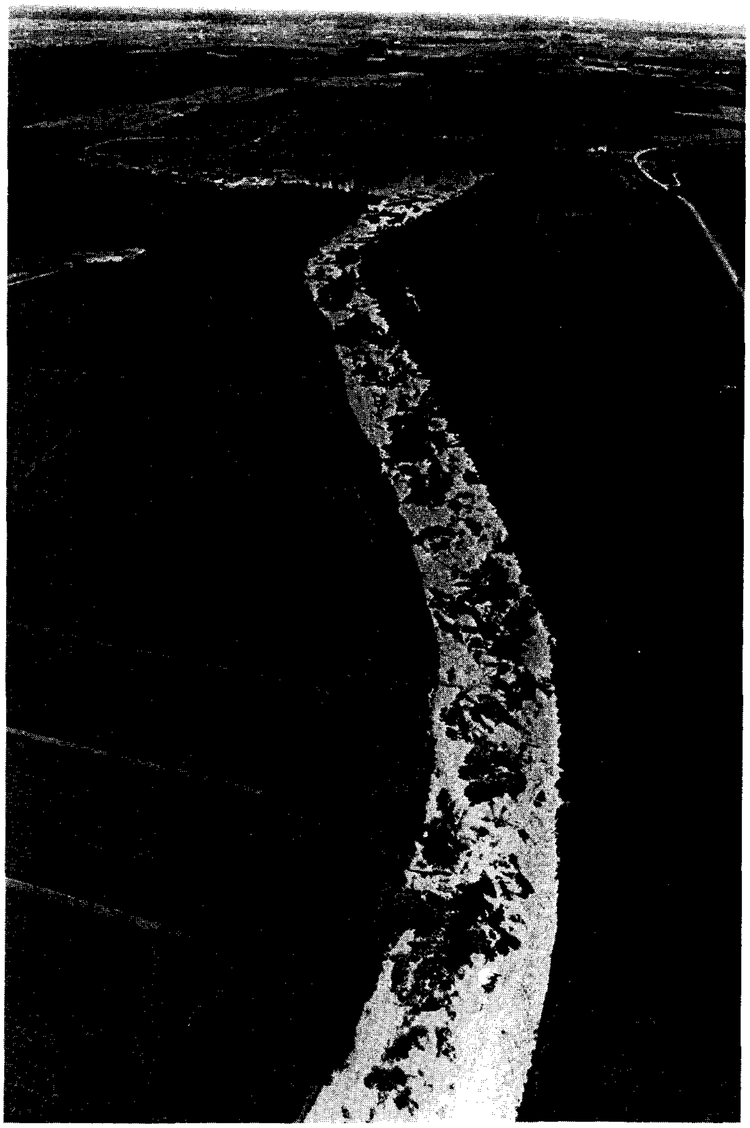

FIG. 9 . Aerial view of landslide debris in the channel of the South Nation River downstream of landslide crater, which is visible at top left. Photograph taken on June 23, 1993.

who rely upon the South Nation River for agricultural and domestic water supplies. From June 20 to 23 while the South Nation River was still impounded behind the landslide debris, raw water tests at the Plantagenet water treatment plant, about 33 km downstream in the town of Plantagenet, revealed turbidity levels of 24–92 NTU (nephlerometric turbidity units), well within normal ranges (<150 NTU) (J. Breen, personal communication, 30 June 1993).

Following the overtopping of the landslide dam, grab samples of the river water and readings at the plant over the next several days revealed turbidity levels in the 1000–1500 NTU range. By Friday, June 25, turbidity levels had subsided to the 170–500 NTU range, but unfortunately all water sampling was restricted to the raw water intact pipe where suspended sediment may have settled to some degree prior to sampling. On Monday, June 28, turbidity in the raw water intake had reached normal levels (42–91 NTU).

Overall, the Lemieux landslide caused a marked increase in river turbidity that lasted several days, but not until the river overtopped the impoundment. In the near future, Plantagenet water treatment plant officials expect turbidity levels of the river to again increase following significant rainfall–runoff periods (J. Breen, personal communication, 30 June 1993).

Triggers

There was no obvious trigger for the Lemieux landslide. No earthquake was recorded in the region at the time of the landslide (R.J. Wetmiller, Geological Survey of Canada, personal communication, 1993). The stage recordings of the South Nation River discussed above do not show any dramatic change in water level that may have initiated either flood-related erosion or a rapid drawdown failure in the riverbank (cf. the 1971 landslide). The preslide discharge of the South Nation River was 22.4 m^3/s, higher than the 12.7 m^3/s average for June but well below the mean annual discharge of 42 m^3/s (Water Survey of Canada 1990).

Weather immediately prior to the landslide was relatively unexceptional. During June 1993, Ottawa International

FIG. 10. Landslide debris consisting of remoulded spoil and clay blocks in the channel of the South Nation River upstream of landslide crater. Photograph taken on June 21, 1993, from County Road 8 bridge (see Fig. 1) looking upstream.

Airport received 101.4 mm of rainfall, which is in excess of the June average of 76.9 mm. In the week preceding June 20, rainfall was received on 3 of the 7 days, including June 15, which received 24.2 mm, the highest daily total for the month, but only 0.2 mm of rainfall was experienced the day before the landslide (June 19). On June 20, 15.8 mm of rain fell at the airport, with much of this precipitation falling after midday. It continued to rain on the 2 days following the landslide, when 8.4 and 5.2 mm fell on June 21 and 22, respectively.

The nature of the weather in the winter prior to the landslide has yet to be evaluated in detail. According to Brooks et al. (1994) the period between January and June 1993 was the wettest (in terms of total precipitation) first half year on record since 1947. It was also characterized by late heavy snowfall in March and April and a rapid melt during the latter part of the spring. Immediately following the landslide, standing water on pasture lands was visible in the general area of Lemieux and indicated that the water table was very high. It presumably was also very high on June 20 at the time of the landslide.

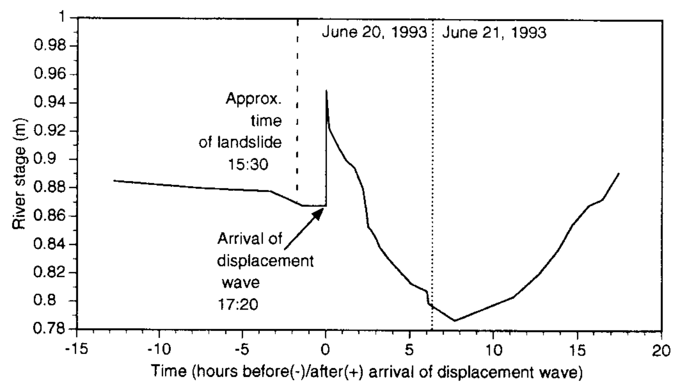

FIG. 11. River level at the Plantagenet stage recorder, 28.4 km downstream of the landslide. The water surface of the South Nation River rose abruptly by 0.082 m at 17:20 June 20 (110 min after the beginning of the landslide) in response to a displacement wave generated by landslide debris flowing down the South Nation valley. After passage of this wave, stage fell gradually to 0.787 m, reflecting the impoundment of the river by the landslide debris. The rise in stage, beginning after 01:00 June 21, reflects rainfall being routed through those areas of the watershed unimpeded by the landslide (data courtesy of Environment Canada).

Comparative retrogressive behaviour

The 1993 Lemieux landslide may be compared to the 1971 South Nation River landslide (Table 2).

It has been suggested by Mitchell (1978*a*, 1978*b*) that highly retrogressive earthflows only occur where the stability number N_s ($N_s = \gamma H/C_u$) at some depth within the slope exceeds 6. For the Lemieux earthflow, for an average cap unit weight $\gamma = 17.16$ kN/m^3, height of bank $H = 23$ m, and minimum undrained shear strength C_u of about 41 MPa for the soft marine clay, a value of $N_s = 9.6$ is obtained.

The extent to which retrogressive distance can be predicted is of considerable importance to land-use planners. One such empirical method has been proposed by Mitchell (1978*a*, 1978*b*) in which the retrogression distance from the crest of the slope (R; see Fig. 2, Mitchell 1978*a*) is predicted on the basis of the value of the stability number N_s. For $5 \leq N_s \leq 12$, R is approximated by

[1] $R = 100(N_s - 4)$

TABLE 2. Comparison of 1993 Lemieux landslide with the 1971 South Nation River landslide

	Area (ha)	Riverbank height H (m)	Retrogression R^a (m)	R/H	Volume (10^6 m^3)
1971 South Nation[b]	27.7	23	421	18.30	7.0
1993 Lemieux	17	23	555	24.13	2.8

[a]Retrogression measured from the crest of the prelandslide slope.
[b]Based on Mitchell (1978*b*).

For the Lemieux landslide, [1] yields a retrogression distance R of 560 m, which corresponds almost exactly to the 555 m of retrogression measured from the crest of the slope.

Conclusions

The 1993 earthflow (est. volume 2.8×10^6 m^3) in sensitive clay at Lemieux is the fourth major landslide to have taken place along a 4.6 km stretch of the South Nation River since 1895. This is the highest concentration of large ($>1 \times 10^6$ m^3) historical sensitive-clay flows in the St. Lawrence Lowlands and is suggestive of conditions very favourable for sensitive-clay flow occurrence. Along this stretch, the river is incised about 23 m into the surrounding flat terrain, and borehole data indicate that a zone of soft, sensitive clay exists beneath a stiffer cap of silts and sands, in which the liquidity index exceeds unity and sensitivities range from 4.3 to 11.4. The landslide involved a total area of 17 ha and retrogressed a total of 680 m from the channel of the South Nation River, 555 m of this total being from the crest of the prelandslide slope. Landslide debris exhibited dramatic mobility in flowing both up and down the South Nation valley. Eyewitnesses, and the measurement of the displacement wave 28.4 km downstream, suggest that the initial phase of the landslide was rapid. The debris dammed the South Nation River, but no outburst flood was generated after the river overtopped the impounding debris. No trigger is discernible for the landslide, although it occurred near the end of the wettest first half year on record since 1947. Direct and indirect costs of the landslide to date are approximately Cdn. $2.5 million.

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