Géographie physique et Quaternaire

Some constraints on the severity of landslide penetration in sensitive deposits
Les contraintes à l'ampleur des glissements en zones constituées de matériaux sensibles
Die Spannungen bei Erdrutschen in Gegenden mit empfindlichen material

M. A. Carson et Ginette Lajoie

Volume 35, numéro 3, 1981

URI : https://id.erudit.org/iderudit/1000541ar
DOI : https://doi.org/10.7202/1000541ar

Aller au sommaire du numéro

Éditeur(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (imprimé)
1492-143X (numérique)

Découvrir la revue

Citer cet article

Carson, M. A. & Lajoie, G. (1981). Some constraints on the severity of landslide penetration in sensitive deposits. *Géographie physique et Quaternaire*, *35*(3), 301–316. https://doi.org/10.7202/1000541ar

Résumé de l'article

Dans les zones constituées de matériaux sensibles, il s'avère dans plusieurs cas que la topographie de la vallée exerce un contrôle sur l'ampleur de la rétrogression lors d'un mouvement de masse. Des études de cas et des considérations théoriques viennent illustrer cette hypothèse. Afin de prédire la distance de la retrogression à partir des caractéristiques topographiques d'une vallée, une formule est proposée. Le contrôle qu'exerce cette contrainte topographique s'expliquerait par une liquéfaction *limitée* des débris dans la plupart des glissements. La discussion porte aussi sur les cas où le recul cesse avant que cette limite imposée par la topographie ne soit atteinte. La nature de la rupture initiale semble alors constituer un facteur déterminant pour l'avortement du processus de rétrogression. Dans les cas montrant un recul qui excède largement cette limite topographique, on insiste sur l'importance du degré de liquéfaction des débris comme condition préalable. Les données présentées démontrent que la résistance initiale au cisaillement du dépôt non drainé influence grandement ce degré de liquéfaction. Dans un dernier temps, on étudie la possibilité que certaines ruptures avec rétrogression aient été des glissements en bloc où la masse se serait morcelée après rupture. Cependant, ces pseudo-rétrogressions seraient plutôt rares.

Géographie physique et Quaternaire, 1981, vol. XXXV, n° 3, p. 301-316, 15 fig., 1 tabl.

SOME CONSTRAINTS ON THE SEVERITY OF LANDSLIDE PENETRATION IN SENSITIVE DEPOSITS

M.A. CARSON and Ginette LAJOIE, respectively, Department of Geography, McGill University, 605, rue Sherbrooke ouest, Montréal, Québec H3A 2K6, and Les Consultants SOGEAM Inc., 460, rue Saint-Charles ouest, Longueuil, Québec J4H 1G4.

ABSTRACT Theoretical considerations and case-studies are presented to show that, in many cases, the severity of retrogression of an unstable valley slope, in areas of sensitive muddy sediment, is controlled by the topography of the valley. A formula is offered to predict the distance of retrogression from topographic attributes of valleys. It is suggested that most retrogressive landslides in sensitive sediments involve only limited liquefaction of the spoil, and it is for this reason that retrogression is controlled by this topographic constraint. Those situations in which retrogression stops before this limit is reached are also discussed: one important factor which can determine whether or not such aborted retrogression will occur appears to be the nature of the first-time slide. Those situations in which retrogression can exceed this topographic limit are briefly examined as well: attention is focussed on the importance of spoil liquefaction as a prerequisite for such excess landslide retrogression. Data are presented which indicate that the initial undrained strength of the sediment exerts a major control on the degree of spoil liquefaction. Finally the possibility is considered that some assumed retrogressive failures were in fact flake slides in which the slide mass disintegrated after failure. Such 'retrogressive facsimiles' are considered to be rare.

RÉSUMÉ *Les contraintes à l'ampleur des glissements en zones constituées de matériaux sensibles.* Dans les zones constituées de matériaux sensibles, il s'avère dans plusieurs cas que la topographie de la vallée exerce un contrôle sur l'ampleur de la rétrogression lors d'un mouvement de masse. Des études de cas et des considérations théoriques viennent illustrer cette hypothèse. Afin de prédire la distance de la rétrogression à partir des caractéristiques topographiques d'une vallée, une formule est proposée. Le contrôle qu'exerce cette contrainte topographique s'expliquerait par une liquéfaction *limitée* des débris dans la plupart des glissements. La discussion porte aussi sur les cas où le recul cesse avant que cette limite imposée par la topographie ne soit atteinte. La nature de la rupture initiale semble alors constituer un facteur déterminant pour l'avortement du processus de rétrogression. Dans les cas montrant un recul qui excède largement cette limite topographique, on insiste sur l'importance du degré de liquéfaction des débris comme condition préalable. Les données présentées démontrent que la résistance initiale au cisaillement du dépôt non drainé influence grandement ce degré de liquéfaction. Dans un dernier temps, on étudie la possibilité que certaines ruptures avec rétrogression aient été des glissements en bloc où la masse se serait morcelée après rupture. Cependant, ces pseudo-rétrogressions seraient plutôt rares.

ZUSAMMENFASSUNG *Die Spannungen bei Erdrutschen in Gegenden mit empfindlichen material.* In Gegenden mit empfindlichen Material, zeigt es sich in mehreren Fällen, dass bei Massenbewegungen die Topographie des Tales eine gewisse Kontrolle über die Ausdehnung der Retrogression ausübt. Man schlägt eine Formel vor, mit der man die Ausdehnung der Retrogression von den topographischen Verhältnissen eines Tales aus, voraussagen kann. Es wird vorgeschlagen, dass die meisten Retrogressionen in empfindlichen Ablagerungen nur eine geringe Verflüssigung des Schuttes haben, und daraus ergibt sich, dass der Zurückschub durch die topographischen Spannungen kontrolliert wird. Die Situationen in welchen der Zurückschub anhaelt, bevor diese Grenze erreicht ist, werden auch erwähnt: ein wichtiger Faktor, der über eine abortive Retrogression entscheidet ist die Art des ersten Erdrutsches. Die Situationen in welchen die Retrogression die topographischen Grenzen überschreitet werden auch kurz geprüft: die Aufmerksamkeit ist hier auf die Wichtigkeit der Verflüssigung des Schuttes als Voraussetzung für solch eine übermässige Retrogression gerichtet. Man gibt Daten, die zeigen, dass die anfängliche, nicht entwässerte Stärke der Ablagerungen eine starke Kontrolle über den Grad der Verflüssigung des Schuttes ausübt. Schliesslich wird die Möglichkeit berücksichtigt, dass einige angenommene Brüche mit Retrogression in Wirklichkeit Lamellenrutsche gewesen sind, in welchen die Rutschmassen nach dem Bruch zerfallen sind. Diese Pseudo-Retrogressionen sind jedoch recht selten.

INTRODUCTION

Scars of landslide retrogression in the sensitive silty-clay deposits of the St. Lawrence and Ottawa River Lowlands, as well as in parts of Scandinavia and elsewhere, are common, and have been studied by civil engineers for decades. Though these scars may differ significantly in size, shape and morphology, and though various names are given to the landslides, *e.g.*, flowslide, earthflow, *coulée d'argile, coulée argileuse*, no satisfactory classification of these retrogressive slides (either generic or genetic) exists.

The present article is not an attempt to classify such landslides. Instead, it segregates these slides into three categories, based on their relative retrogression distance (R/H as defined in Fig. 1), and examines some of the factors — particularly the morphological ones — that affect the amount of retrogression. Although the distance of retrogression is only one aspect of flowbowl size, in those situations involving planning of valley edge areas, with designation of safe "set-back" distances, it is the most important attribute. Previously this topic has been treated both empirically (MITCHELL and MARKELL, 1974) and mechanistically (CARSON, 1979); but in both cases the emphasis was primarily on geotechnical factors, *e.g.*, sensitivity and undrained shear strength of the sediment. It is clear, however, that in many cases, the pre-existing topography of the valley, and even the nature of the initial slide itself, provide definite morphological constraints on the amount of retrogression; these are the points considered here.

I — THE TYPE EXAMPLE: TWO-DIMENSIONAL SPREADING FAILURE

In an idealized situation in which a length of valley slope (W) fails and retrogresses, with constant width, over a distance (R) from the initial slope top; in which the "spoil" from the subsidence and retrogression is pushed away from the site of the failed slope across the valley until blocked by the opposite slope; in which there is no squeezing of the spoil upvalley or downvalley from the site; and in which there is no "bulking" of the spoil relative to the density of the undisturbed sediment; then, continuity requirements dictate that:

$$R.dh = f.(H - dh) + (H - dh)^2 \cot(i) \qquad (1a)$$

$$R/H = (1 - n).((f/dh) + (1 - n).\cot(i)/n) \qquad (1b)$$

in which, as indicated in Figure 1, (dh) represents the amount of subsidence in the flowbowl, H is the height of the valley slope, n is the fractional amount of subsiddence (dh/H), (f) is the width of the valley floor and (i) is the slope angle.

Several examples of this kind of failure have recently been reported in sufficient detail to allow comparison (Table I(a)) of actual retrogression with the amount predicted by Equation 1. At Sköttorp, Baastad and Rigaud there is reasonably good agreement; at South Nation River and Saint-Ambroise-de-Kildare, the wider valley floors permitted rather more "extrusion" of the spoil up and down the valley, thus leading to underprediction of R/H. Nonetheless, in both of these last two cases, the bulk of the spoil was made up of intact blocks of silty-clay (not liquefied), and, as a consequence, the amount of up- and downvalley extrusion (and thus the amount of excess retrogression) was restricted.

The landslide craters at the five sites just mentioned are characterized by a distinctive pattern of ridges roughly parallel to the valley axis, leading us to refer to them as *ribbed landslides.* Scars of older, but similar, slides occur throughout the Ottawa and St. Lawrence Lowlands. One example is the clay belt west of Lachute (Figs. 2, 3). This area has been mapped in some detail (CARSON, 1981), and Figure 4 shows the distribution of deep-seated slips by their R/H value. The morphological data for the larger slides of the Mabel and West Lachute areas are also shown in Table I(b). Again, there is, in general, good agreement between actual amounts of retrogression and the amounts given by Equation 1; there is some "excess" retrogression, but this is small.

On the basis of this limited set of landslides, it would certainly seem that the size of the pre-existing valley (Eqn 1) can exert a strong control on the amount of landslide retrogression, provided that full liquefaction[1] of the spoil does not occur. If this preliminary conclusion could be substantiated with more case studies, it is evident that Equation 1, corrected by an appropriate "safety factor", could be used as an initial guideline in planning safe set-back distances from presently stable slopes.

Unfortunately, though data on R and H have been obtained in previous studies for many landslide scars in southern Québec and adjacent parts of Ontario, other necessary data, namely the subsidence fraction (n), valley floor width (f) and pre-failure slope angle (i) are not available at these sites, and thus prevent substantiation of Equation 1 over a larger sample size. Nonetheless, reasonable limits may be set for these other variables,

1. The term "liquefaction" is used here to denote the conversion of the spoil to a liquid mud by remoulding. As such, it is a more general term than that employed in soil mechanics, where it refers specifically to the attainment of a fluid state in saturated granular material by the development of pore pressures sufficient to eliminate intergranular stresses. Spoil liquefaction, as used in this article, may occasionally involve liquefaction of granular material as understood in soil mechanics, but also includes conversion of clay to a fluid state by remoulding.

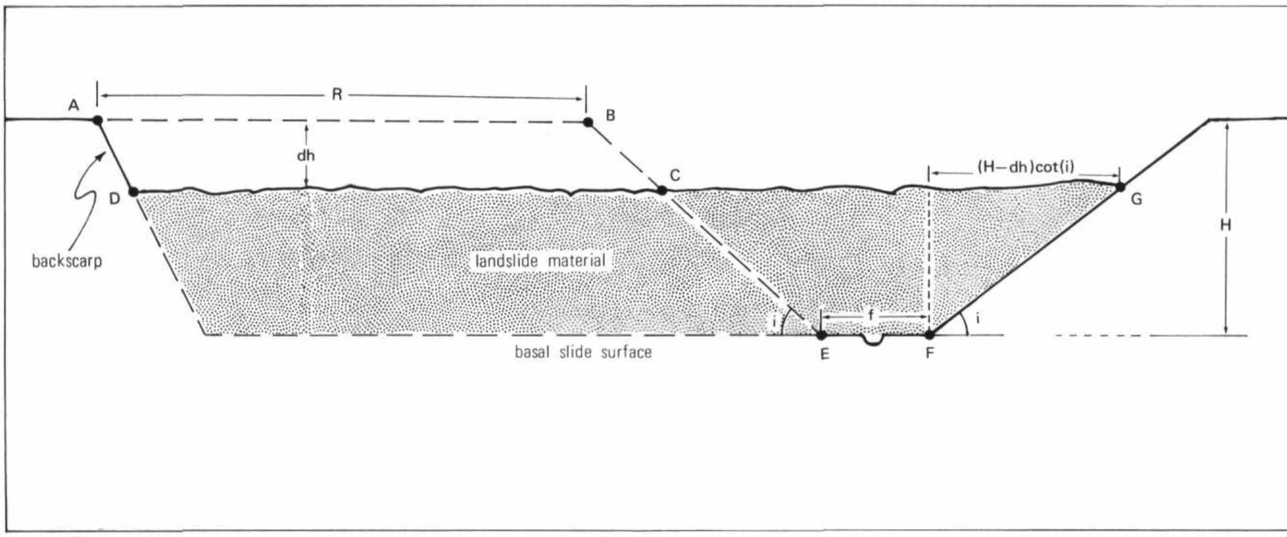


FIGURE 1. Schematic cross-section of landslide scar and infilled valley: definition diagram for parameters of Equation 1.

Coupe transversale schématique d'un glissement et de la vallée remblayée. Les paramètres de l'équation n° 1 sont indiqués sur le schéma.

TABLE I

Morphological data from earthflow sites

Slide	Date	f (metres)	H (metres)	dh (metres)	n	cot(i)	R	R/H = r	r'	r/r'
(a)										
Sköttorp	1946	35	21	8	.38	3	160	8	6	1.3
South Nation R.	1971	105	24	9	.37	2.7	385	16	10	1.6
Baastad	1974	20	30	15	.50	3.2	100	3.3	2.3	1.4
St-Ambroise	1975	100	20	9	.45	3	300	15	8	1.9
Rigaud	1978	15	15	7	.45	3.1	50	3.3	3.2	1.0
(b)										
Mabel (C)	?	40	16	4	.25	2.9	400	25	14	1.8
Mabel (D)	?	40	15	4	.27	3	320	21	13	1.6
Mabel (E)	?	40	14	6	.43	3.7	160	11	7	1.6
W Lachute (G)	?	80	12	4	.33	3	230	19	17	1.1
W. Lachute (H)	?	80	11	4	.36	4.3	190	17	17	1.0
W. Lachute (I)	?	80	12	4	.33	3	215	18	17	1.0
(c)										
Maskinongé	1840	90	24	7	.29	3	900	38	14	2.6
Ogdensburg (A)	?	50	14	3	.22	2.8	660	47	21	2.2
(d)										
Selnes	1965	30	12	7	.58	3	140	12	2.6	4.5
St-Thuribe	1898	220	14	9	.64	3	850	61	9	6.8
Ullensaker	1953	10	6	5	.83	3	130	22	0.4	54
St-Jean-Vianney	Ap. 1971	20	40	35	.87	1.0	120	3	0.1	30
St-Jean-Vianney	May 1971	125	28	25	.92	1.0	300	11	0.4	28

N.B. r' is the predicted value of R/H from Equation 1;
r/r' is the "excess" retrogression ratio;
all values of cot(i) equal to 3 are assumed values;
mean retrogressive distance (R) is in metres.

FIGURE 2. Air photograph of flowbowl (Mabel (C) in Ogdensburg-Lachute region, Québec.

Photographie aérienne d'un glissement (Mabel (C)) de la région d'Ogdensburg-Lachute, Québec.

FIGURE 3. Air photograph of flowbowl (West Lachute (H)). Note well-defined "ribbed" microrelief, and full translation of spoil across valley.

Photographie aérienne d'un glissement (à l'ouest de Lachute (H)). Une série de rides transversales ainsi que le déplacement complet de la masse vers le versant opposé de la vallée se distinguent nettement sur la photo.

and some attempt to put limits on R/H, using Equation 1, may then be made. For example, with $0.25 < n < 0.5$ and $15° < i < 30°$, Equation 1 yields

$$0.5\,(f/dh) + 0.9 < R/H < 0.75\,(f/dh) + 8.4 \qquad (2)$$

a range which still depends considerably upon both the absolute amount of subsidence and the valley floor width. However, even with *extreme* values of $4m < dh < 16m$ and $20m < f < 200m$, this two-dimensional continuity restraint, expressed in (2), should keep R/H in the range

$$1.5 < R/H < 46; \qquad (2a)$$

and, for valleys of common width, say $f = 100m$, the range would be only

$$4 < R/H < 27. \qquad (2b)$$

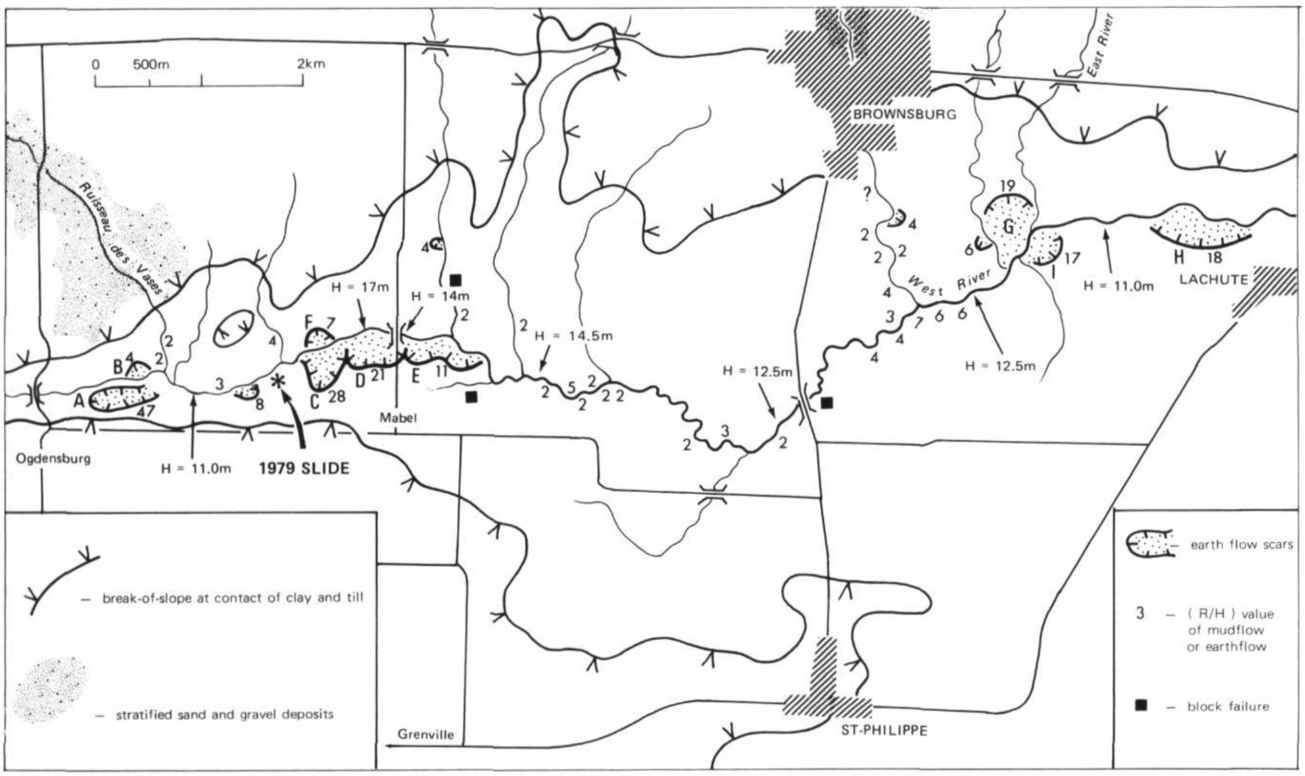


FIGURE 4. Distribution of deep-seated landslide scars in Ogdsenburg-Lachute region, Québec, shown by R/H value. Retrogressive landslide of November, 1979, is shown by asterisk.

Répartition des glissements profonds dans la région d'Ogdensburg-Lachute, Québec, illustrée à l'aide du rapport R/H. L'astérisque montre le glissement avec rétrogression qui eut lieu en novembre 1979.

Previously, MITCHELL and MARKELL (1974) collected data on R/H for eleven landslide areas in the Ottawa Valley area, with river valleys in which the width approximated 100 metres; their findings are included in Figure 5. Though there is no certainty that all the scars examined by them represent retrogressive landslides (and though there appear to be many errors in their data), it is worth noting that less than 15 percent of the sites showed R/H greater than 20 and only 4 sites (out of more than 100) showed excessive retrogression (R/H > 27). Figure 5 also shows the frequency of R/H values for flowslide scars in the lower Maskinongé Valley (LAJOIE, 1978) restricted, except for the 1840 slide, to values of 4 to 24. Finally, in order to put these ancient flowbowl scars in perspective, the R/H values of some more recent retrogressive slides are also shown in the figure. Again, the majority of them show amounts of retrogression well within the limits of that predicted by Equation 2 (for f = 100m), although there are a few which show considerable "excess" retrogression. This feature will be examined later.

II — ABORTED RETROGRESSION

Examination of the landscape of clay areas, either in the field or using air photographs, indicates that there are many cases in which retrogression stopped well before the valley constraint of Equation 1 was reached. This is referred to here as aborted retrogression. In some of these cases, such as an extremely wide valley floor (*e.g.*, Green Creek, Ontario), a large river (*e.g.*, Nicolet, 1955), or along coastal cliffs (*e.g.*, Havre-Saint-Pierre, 1980), the theoretical distance of retrogression would be huge, and other (non-morphometric) factors would stall the retrogression before the morphological constraint occurs.

Foremost among these non-morphometric factors is probably spatial change in the character of the sediment. An obvious case is that in which retrogression is halted by till or even rock. At Saint-Jean-Vianney (not a ribbed slide), though the retrogression was well in excess of the topographic limit of Eqn 1 (and is discussed later), the limit to retrogression appears to have been dictated by a change to sediment that included thick lenses of sand (Chagnon, 1981, pers. comm.). And at Saint-Ambroise, in which R/H corresponded reasonably well with that predicted by Eqn 1, it must also be acknowledged that borehole data (LEBUIS, 1977) indicate that the halt in retrogression coincided with an abrupt decrease in sensitivity (increase in

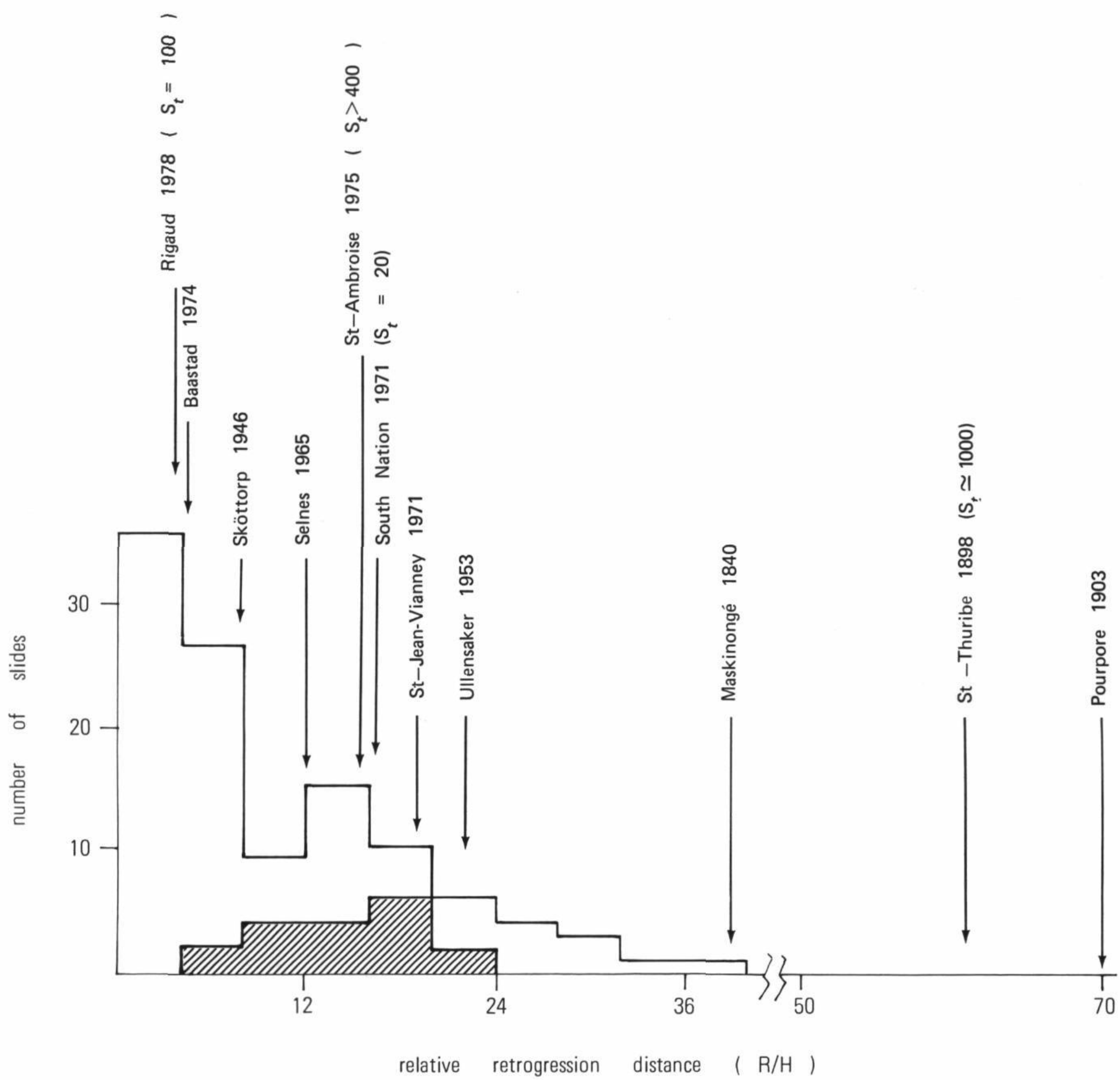


FIGURE 5. Frequency distribution of R/H values of landslide scars for valleys in Ottawa area (unshaded; MITCHELL and MARKELL, 1974) and for Maskinongé Valley, Québec (shaded; LAJOIE, 1978), together with R/H values of selected historic slides.

Fréquence de distribution des valeurs de R/H pour des glissements rencontrés dans certaines vallées de la région d'Ottawa (sans trame: MITCHELL et MARKELL, 1974) et dans la vallée de la rivière Maskinongé (en grisé; LAJOIE, 1978). Les valeurs de certains glissements historiques ont été incorporées à l'histogramme.

remoulded strength by fall cone) in the area behind the eventual backscarp.

In many cases, however, it is apparent that retrogression is aborted without any obvious change in sediment properties or in the topography of the area behind the slide. And even in very small valleys, retrogression often appears to have stopped well before the limit imposed by the valley.

As an example of this last point, Figure 4 shows that in the Lachute field region, most scars have R/H values in the range 2 to 6; and yet, on the basis of valley geometry, retrogression should have been able to proceed to R/H values greater than 10. Unfortunately, it is impossible to understand why this abortion of the regrogression process should occur unless examination of the landslide scar is made very soon after the failure. Such post-mortem analyses of slides immediately after failure are not widely reported in the literature. In November 1979, however, one such failure, involving aborted retrogression, occurred in the Mabel (Lachute) area; and the site was subjected to a fairly detailed field study within two days. Figures 6 and 7 are front and side photo-mosaics of the slide; Figure 8 is a cross-section based on field levelling, together with Nilcon vane tests to locate the failure surface at the base of the spoil; Figure 9 shows the valley in July, 1979 prior to failure.

From these field data, it is apparent that failure comprised two stages: 1) a classic circular slip through the top and foot of the slope, affecting a downvalley length of 45 m, and achieving a rotation of 35 degrees, to expose a new slope of about 15 m; 2) retrogression of that backscarp for a distance of about 35 m.

The initial failure, in effect, turned the original valley slope upside-down, orienting the intact block against the newly exposed backscarp. The spoil of the retrogression, although highly fissured, showed distinctive "ridges" and linear strips of the former terrace similar to those reported in other larger ribbed slides.

The slide occurred in an area of sensitive clay (150-200 by fall cone) and (Fig. 4) close to the large scars of several ancient earthflows. The R/H value was, however, only two. Though the potential obviously existed for severe retrogression, the spoil was stopped from spreading fully across the valley floor by the overturned block left by the first slip. As shown in Figure 8, the spoil was forced to mount this new reverse slope and eventually it became stabilized. In fact, given this field example, it is difficult to see how the classic rotational first-time slip *could* lead to severe retrogression, unless

FIGURE 6. Front view of 1979 Mabel landslide near Lachute. The upstream (right) side of the crater is flanked by a small ravine. Retrogression was slightly oblique to the line of sight with extension towards the top right, and movement of spoil towards the bottom left. The front "wall" of clay is sediment previously beneath stream level.

Vue de face du glissement de Mabel de 1979, près de Lachute. Un petit ravin recoupe le flanc amont (droit) du glissement. Le recul s'est effectué un peu obliquement par rapport à l'axe de la prise de vue, avec une extension vers la droite, en haut de la photo. Les débrisse sont déplacés vers le bas à gauche. L'argile à l'avant-plan se retrouvait à l'origine sous le niveau du cours d'eau.

FIGURE 7. Side view of 1979 Mabel landslide looking downstream (east). The locations of vane tests (Fig. 8) are shown by number. The slickensided blocks near #4 represent the remains of an "*arête*" which toppled forwards during the translation to the left. A second ridge (fissured and largely collapsed) passes through #6.

Vue latérale vers l'aval (direction est), du glissement de Mabel de 1979. Les chiffres indiquent la position des essais au scissomètre (fig. 8). À proximité de l'essai n° 4, il ne subsiste que des blocs striés d'une crête qui a basculé vers l'avant, lors de sa translation vers la gauche. L'essai n° 6 traverse une seconde crête fissurée et considérablement disloquée.

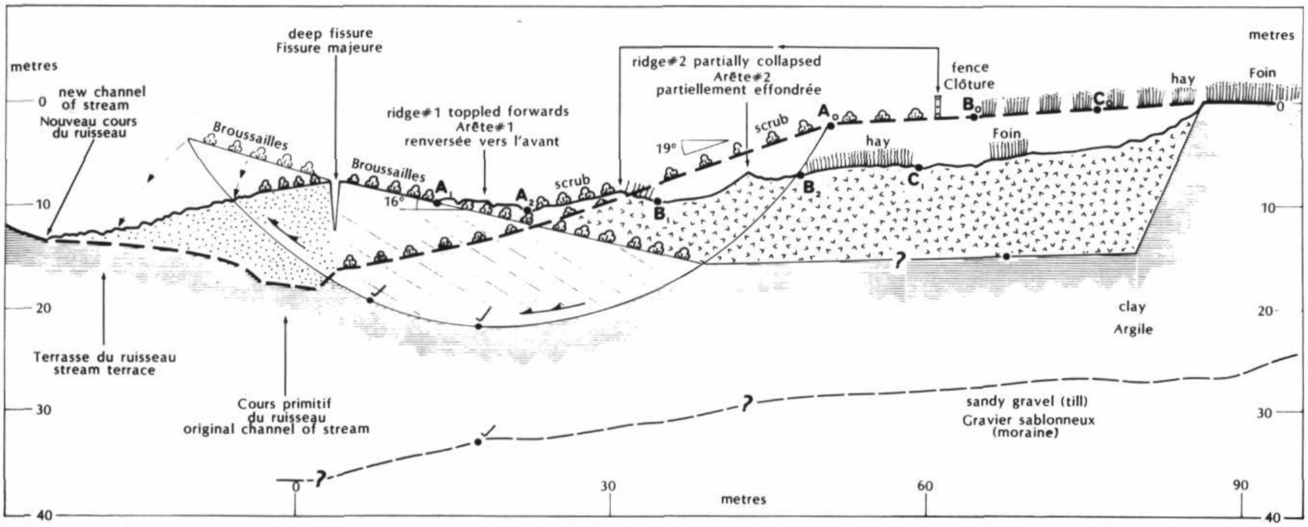


FIGURE 8. Longitudinal section of 1979 Mabel slide showing (a) intact part of initial rotational block (striped); (b) front part of rotational block (stippled) forced above stream bed and subject to collapse; (c) debris from retrogression (v-stipple) forced up overturned slope. A_2B_1 is the ground surface formerly adjacent to A_0B_0; B_2C_1 is the ground surface formerly adjacent to B_0C_0. The contact with till is based on seismic refraction confirmed at one site by the Nilcon vane. Other solid points (3) represent positions of the failure surface based on Nilcon vane tests.

Coupe longitudinale du glissement de Mabel de 1979 montrant (a) la portion intacte du compartiment qui a subi la rotation initiale (partie hachurée); (b) la partie frontale d'un bloc instable qui a pivoté et qui a été refoulé au-dessus du lit du cours d'eau (en pointillé); (c) les débris du glissement injectés le long du versant qui a basculé (trame avec chevrons). La ligne A_2B_1 correspond à la surface du sol qui à l'origine était adjacente à A_0B_0, et la ligne B_2C_1 était adjacente à B_0C_0. Le plan de contact avec le till a été établi par réfraction sismique et sa position a été confirmée par un essai au scissomètre à un site. Les autres points (3) marquent la localisation de la surface de rupture évaluée à partir d'essais au scissomètre Nilcon.

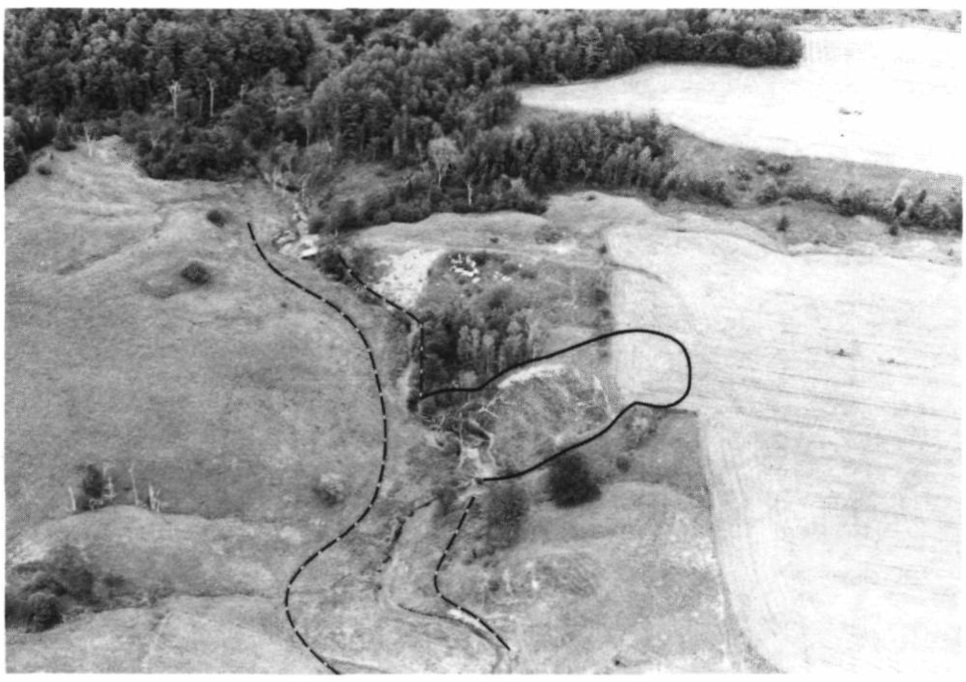


FIGURE 9. Photograph of Mabel slide area taken in July 1979, four months prior to failure, looking east (downvalley). Solid line delineates slide area; dashed lines denote limits of floodplain.

Secteur du glissement de Mabel photographié en juillet 1979, quatre mois avant la rupture. Vue vers l'est (aval). La ligne pleine circonscrit le glissement et les tirets délimitent la plaine alluviale.

the initial block could, somehow, be translated forwards instead of, or as well as, undergoing rotation. Because rotational first-time slips are commonplace, it may well be that the other small scars in the Lachute region (Fig. 10), and elsewhere, reflect this peculiar aborted form of retrogression.

III — EXCESS RETROGRESSION

On the other hand, while in many cases landslide retrogression becomes aborted before attaining the full "run-out" allowed by the valley cross-section, there are, at the other extreme, occasional spectacular earthflows which retrogress much further than might be predicted from Equation 1. We describe this as excess retrogression. Examination of case studies of this type leads us to infer two possible factors which permit excess retrogression, with R/H greater than, say, thirty.

The first of these relates to the local topographic setting of the slide area within the valley. Under normal circumstances excessive runout of spoil requires, firstly, a translation across the valley floor and, then, a change in direction of movement of the order of ninety degrees for travel up- or downvalley. In those circumstances, the direct thrust upon the spoil is across the valley, and it is not difficult to appreciate, at least qualitatively, that the up- or downvalley thrust component is quite small. However, in exceptional topographic circumstances (*e.g.*, just upstream from a bend: Fig. 11), the "cross-valley" thrust on the spoil in the crater is aligned almost directly on the downvalley trajectory of the spoil. In these cases, the resistance to movement of the spoil is much less, and more retrogression than usual would be expected. This appears to have been the case in the 1840 Maskinongé slide and in the ancient Ogdensburg slide (Table I(c)).

The second, and far more important, situation in which excessive retrogression occurs, seems to involve more rapid, and much more complete, remoulding of the silty-clay sediment than so far described, in effect a "liquefaction" of the spoil. In contrast to the South Nation type slide (in which only small amounts of "liquefaction" occurred, producing fluid mud only along the shear surfaces which separated the rigid blocks of sediment in the spoil), the slides at Rissa, Ullensaker and Selnes (in Norway) and Saint-Jean-Vianney and Saint-Thuribe involved conversion of virtually all of the debris into a liquid mud which flowed, ponded, and burst downvalley. In these cases (Table I(d), the "run-out" was much greater, and retrogression was much less impeded by the congestion of spoil in front of the slide area.

The *mechanism* of retrogression in these slides (which are called *coulées* here, being quite different morphologically from ribbed slides) may not be radically different from the "ribbed" flowbowl made up of intact blocks. For example, photographs of the 1898 Saint-Thuribe slide by DAWSON (1899, opp. p. 488) show that, while most of the debris "liquefied", there were large blocks of sediment, identical in appearance

FIGURE 10. Photograph of area immediately upstream of 1979 Mabel slide showing small scar (dotted) on north (right) valley side (R/H = 3) characteristic of the Lachute region.

Sur le flanc nord (à droite) de la vallée apparaît en pointillé une petite cicatrice (R/H = 3) typique de la région de Lachute. Cette zone se situe légèrement à l'amont du glissement de Mabel en 1979.

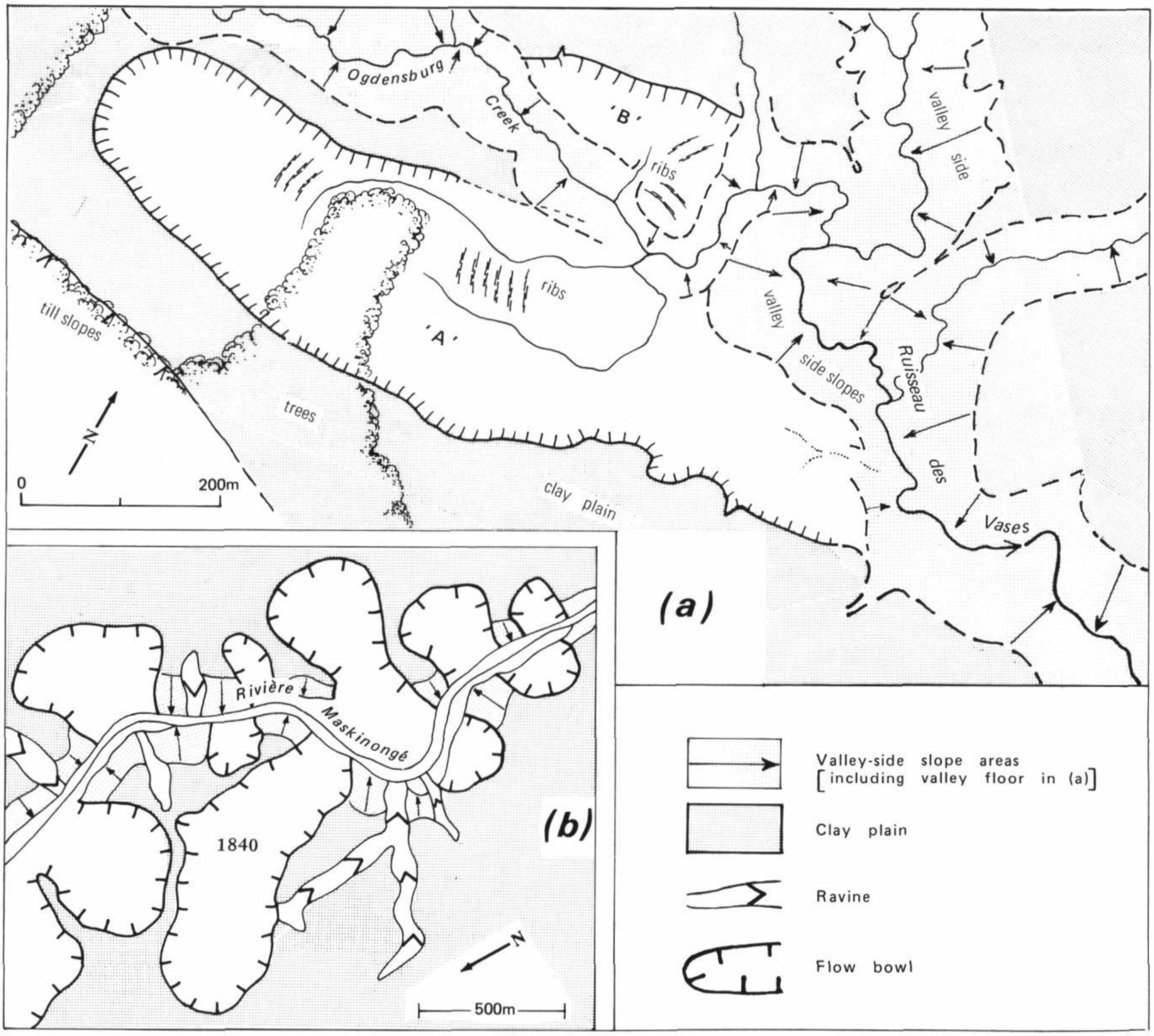


FIGURE 11. Topographic setting of (a) Ogdensburg earthflow and (b) 1840 Maskinongé earthflow.

Contexte topographique d'une ancienne coulée à Ogdensburg (a) et de la coulée de 1840 affectant la rive droite de la rivière Maskinongé (b).

to those at South Nation, Rigaud, and elsewhere, within the fluid mud and incorporated in its downriver flow out of the crater. As a further example, photographs of the 1955 Nicolet slide by BÉLAND (1956, p. 149) show that, although much of the spoil may have liquefied, nonetheless, large, intact and upright ridges of sediment were also found in the crater. The same pattern of ridges is shown in 1: 4800 air photographs published by le Ministère des Terres et Forêts (377-24,-25,-26). The same point appears to be indicated in the 1980 Havre-Saint-Pierre slide on the north shore of the Gulf of St. Lawrence (Fig. 12): the western part of the crater possesses the distinctive morphology of a ribbed slide, while the eastern part superficially resembles a coulée. Finally, similar ridges were noted and photographed by JANBU (1980, p. 483) from the Rissa slide in Norway, a slide in which virtually all of the spoil remoulded to liquid mud. Moreover, Janbu's explanation of these ridges is not radically different from that suggested previously for ridges in eastern Canadian slides (CARSON, 1977).

It might also be added that the presence of these ridges in slide craters is not restricted to one particular type of sediment. They occur in massive silty clay overlain by laminated clay and sand (Nicolet), banded clayey

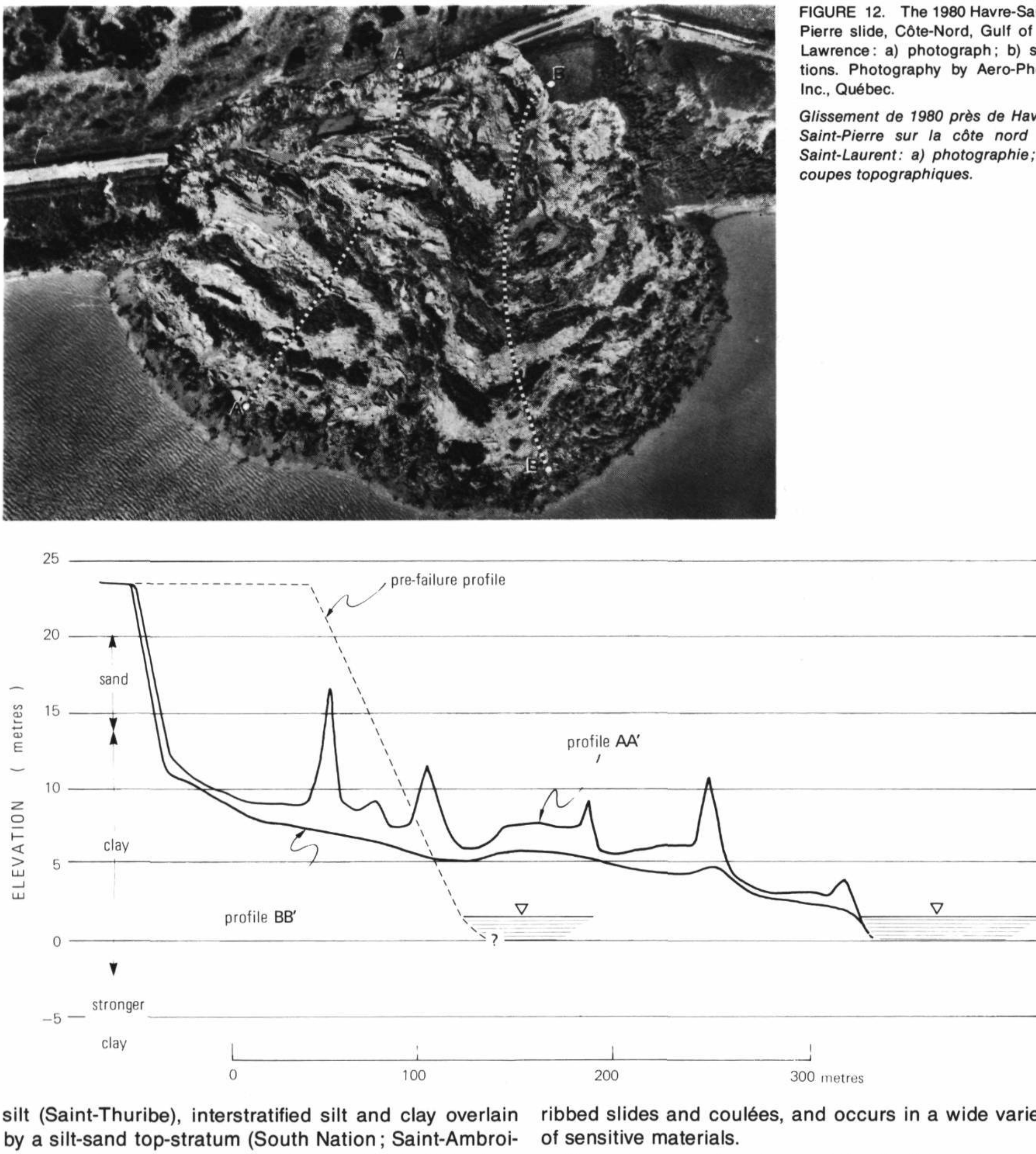


FIGURE 12. The 1980 Havre-Saint-Pierre slide, Côte-Nord, Gulf of St. Lawrence: a) photograph; b) sections. Photography by Aero-Photo Inc., Québec.

Glissement de 1980 près de Havre-Saint-Pierre sur la côte nord du Saint-Laurent: a) photographie; b) coupes topographiques.

silt (Saint-Thuribe), interstratified silt and clay overlain by a silt-sand top-stratum (South Nation; Saint-Ambroise), as well as massive clay with occasional silt laminae (Rigaud). The degree of preservation of these ridges does vary considerably from one slide to another, and appears to be controlled by the ease with which the spoil liquefies, as discussed below. Our analysis of many case-studies leads us to believe that a full range of landslide craters exists between the two limiting types of ribbed slides and coulées, and occurs in a wide variety of sensitive materials.

Sometimes, coulées leave distinctly "clean" craters, with virtually all the liquefied spoil having flowed down-valley (*e.g.*, Saint-Jean-Vianney, Rupert River First Rapids): these are extreme cases, however, and appear to be associated with a basal failure plane that is perched well above the level of the slope base, thus facilitating evacuation of material from the crater.

The key feature in the case of coulées is simply the ease with which the sediment of the spoil collapses into a fluid state. This remoulding not only affects the slickensided surfaces of the intact blocks, but also the blocks themselves. Why this should occur has still to be established with any certainty. There is some indication that complete liquefaction (and hence excess retrogression) requires extra-sensitive sediment: the sensitivity of the material at Saint-Jean-Vianney, Ullensaker and Saint-Thuribe (Fig. 5) was appreciably higher than that at Rigaud, Sköttorp and South Nation River, for instance. On the other hand, the actual mechanics of the "remoulding" process during landslides, *i.e.*, the stresses involved in the transformation from the undisturbed to fully-remoulded states, have received little attention from civil engineers.

Moreover, stratigraphic considerations may be significant in determining whether or not sufficient remoulding of the spoil to allow the development of a coulée can occur. For example, although the basal sediment in the slides at Furre (1959) and Baastad (1974), in Norway, was "quick", the material above the basal part, forming the bulk of the spoil, was only of low or medium sensitivity, and prevented liquefaction.

It seems probable, however, that other factors besides extreme sensitivity (throughout the full depth of the slide mass), are required for a high degree of liquefaction of the spoil of a landslide. At Saint-Ambroise, for instance, where sensitivity by fall cone exceeded 400 (LEBUIS, 1977), there was no evidence of liquid mud at the surface of the ribbed slide mass, in marked contrast to the Ullensaker slide. One *additional* requirement for spoil liquefaction may be a sufficiently low initial (undisturbed) undrained strength to permit the remoulding process to take place. Some support for this view is provided by Figure 13 in which the line Su/H = 2.5

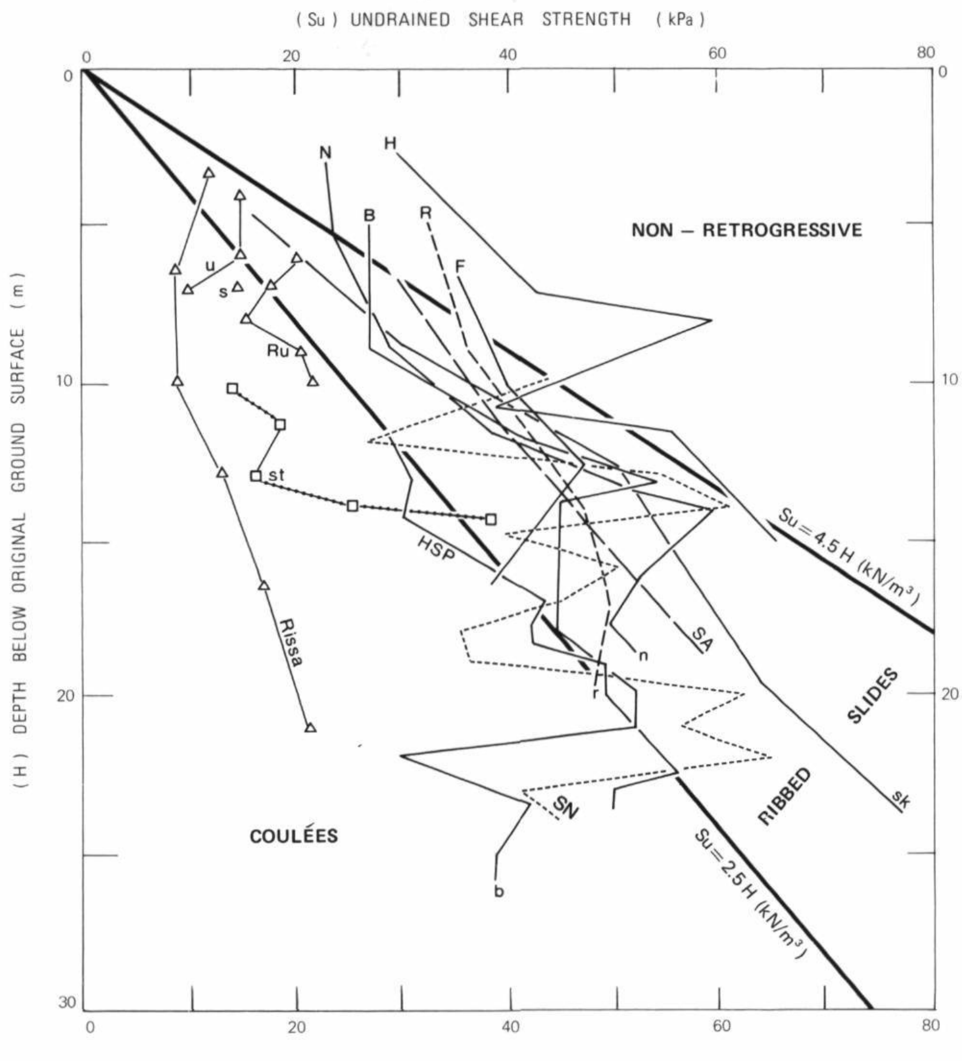


FIGURE 13. Shear strength profiles at landslide sites in recent sensitive sediment. Data may refer to sediment within the flowbowl (lower case abbreviation) and/or a borehole outside the crater (upper case). All profiles extend down only as far as the basal slip surface. Solid lines designate field vane tests; dashed lines denote fall-cone tests; dotted line denotes unconfined compression test (u: Ullensaker; s: Selnes; RU: Rupert First Rapids; st: Saint-Thuribe; N: Nicolet; B: Baastad; R: Rigaud; H: Hawkesbury; SN: South Nation; SA: Saint-Ambroise; F: Furre; SK: Sköttorp; HSP: Havre-Saint-Pierre.

Profils de la résistance au cisaillement mesurée à divers sites de glissements dans des matériaux sensibles. Les valeurs se rapportent aux matériaux du plancher du glissement (abbréviations en lettres minuscules) ou proviennent de sondages effectués à l'extérieur de celui-ci (lettres majuscules). Ces profils ne descendent pas sous la surface de rupture. Les essais au scissomètre sont représentés par des lignes continues, tandis que les tirets désignent les essais au cône suédois et le pointillé se réfère aux mesures de compression simple. (u: Ullensaker; s: Selnes; RU: premiers rapides de la rivière Rupert; st: Saint-Thuribe; N: Nicolet; B: Baastad; R: Rigaud; H: Hawkesbury; SN: South Nation; SA: Saint-Ambroise; F: Furre; SK: Skottorp; HSP: Havre-Saint-Pierre.

kN/m^3 (equivalent to a stability factor of 6.4 to 7.6 for bulk unit weights of 16 to 19 kN/m^3) provides reasonably good separation of coulées and the normal ribbed slide mass. Unfortunately, undisturbed strength data for coulées are meagre; even where they are available, they refer, inevitably, to sediment beneath the slide surface, or behind the backscarp. Such data may not be representative of the material that disappeared during failure. This seems to be true of Saint-Jean-Vianney, the data for which are not shown in Figure 13.

Whatever the reasons for virtually complete liquefaction of the spoil at some sites and not at others, these differences between coulées of the Rissa (Norway) type and the ribbed slides of the South Nation River type are real, and the difference in behaviour of the sediment may exert an important control on the relative retrogression distance. At the same time, it must be noted that the retrogression of coulées, just as ribbed landslides, can be halted at an early stage by a spatial change in sediment type, as indicated in Figure 5 by the below-average R/H values of Selnes, Saint-Jean-Vianney and Ullensaker.

IV — MULTIDIRECTIONAL RETROGRESSION

Implicit in the previous discussion is the view that retrogression proceeds essentially unidirectionally away from the initial slope. In many cases this assumption is clearly valid, but in some it is certainly not so.

The clearest exception to unidirectional retrogression would appear to be the circular "bottlenecked" crater often described in textbooks as the type-example of earthflows in quickclays. Recent inventories of earthflow scars in the St. Lawrence Lowlands (*e.g.*, BELL, 1977) indicate, however, that bottlenecked craters are the exception and not the norm. In the past, bottleneck flowbowls have been "explained" in terms of *radial* retrogression away from a small breach in the crust of a slope (*e.g.*, KARROW, 1972, p. 568). More recently (CARSON, 1977, p. 98), it was suggested that bottleneck flowbowls may represent multi-stage retrogression, first along an axis normal to the slope, and then, secondly, away from this axis. Oblique aerial photographs of the G1-70 slide at the Rupert River First Rapids by BALLIVY *et al.* (1975) show lineations in the spoil that are consistent with the latter view.

Perfectly circular, or even near-circular, bottlenecked flowbowls are rare: many of the bottlenecked craters in fact show considerably irregular outlines. And in some of these cases it is apparent that retrogression proceeded preferentially along one or more axes (Fig. 14). Vivid evidence of this was provided at Rissa in 1978 and is documented in the film of that slide assembled by the Norwegian Geotechnical Institute. Only detailed fieldwork will explain why preferential retrogression along certain axes happens. Whatever the explanation, however, it is clear that in these situations, land-use planning is not merely a question of predicting distances of retrogression, but also direction.

Multi-directional retrogression implies multi-directional movement of the spoil. The internal resistance to evacuation of debris from a crater is therefore greater than in the simple case of unidirectional translation. Given this premise, it would seem probable that multi-directional earthflows require considerable liquefaction of the spoil. In this respect, as well as in plan morphology, therefore, they contrast with the normal type of earthflow in sensitive sediment.

There is some, admittedly limited, evidence to suggest that bottlenecked, multi-directional retrogression is more frequent in the younger sediments of the James Bay-Hudson Bay area than in the older deposits of the St. Lawrence Lowlands. Whether this impression is valid, should be examined, and, if substantiated, investigated.

V — FLAKESLIDES: POSSIBLE RETROGRESSIVE FACSIMILES?

Also implicit throughout this discussion has been the assumption that the large size of the various slides mentioned is due to *retrogressive* failure. In some of these cases (*e.g.*, South Nation River, Saint-Ambroise) the written reports certainly suggest that failure was indeed retrogressive. But only in a few cases, *e.g.*, Nicolet, Turnagain Heights (Alaska) was failure actually observed to be retrogressive by eye-witnesses. The remarkable ridge-graben morphology of the slides at South Nation River, Saint-Ambroise, Baastad, Rigaud and elsewhere leads us to believe, at least as a starting hypothesis, that the mode of failure was the same in all cases.

However, the interpretation of the Baastad slide by GREGERSEN and LOKEN (1979) seems to suggest that this slide was not retrogressive. In fact, their back-calculation of the factor of safety (which yielded a value of 1.03) was based on the instantaneous failure of a single "flake" of clay, with the resistance along the long, gently-sloping basal failure surface assumed to be equal to the undrained strength. Their discussion implied that this intact flake broke up into wedge-prism-shaped blocks immediately after failure, though there is no actual statement to this effect, nor an explanation for the subsidence process.

For completeness, it might be noted that similar spreading failures of unconsolidated lacustrine silt and clay (overlain by sand and gravel) have been reported from Lago Rinihue, Chile, by DAVIS and KARZULOVIC

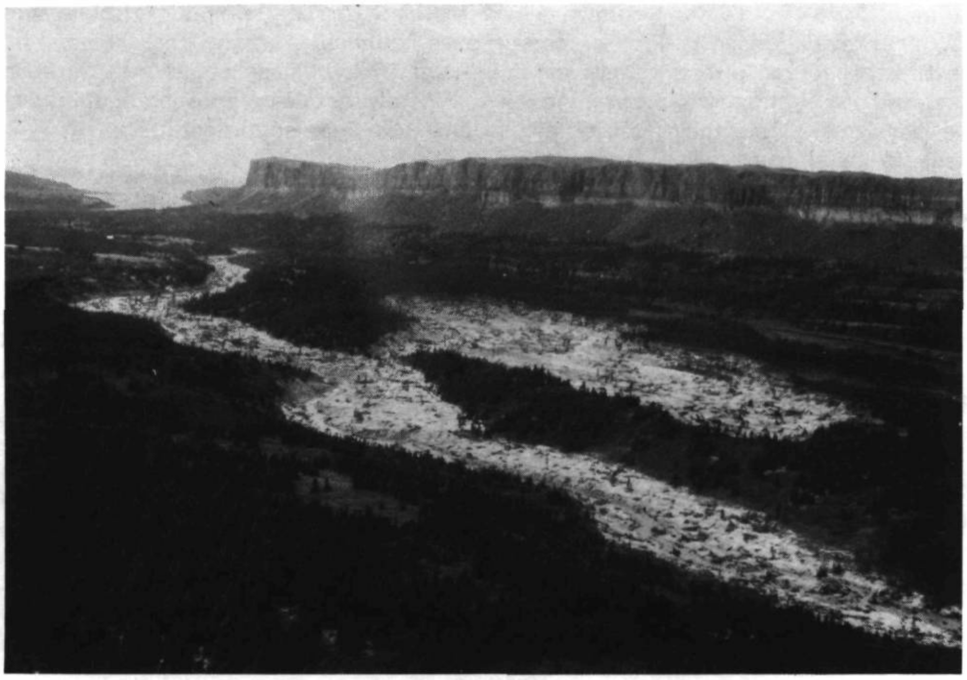


FIGURE 14. Bottleneck crater of a coulée on a tributary of the Petite Rivière de la Baleine, Québec. Note the preferential extension parallel to the valley axis. Photograph taken bh Michel Lapointe.

Coulée avec goulot d'étranglement sur le flanc droit d'un tributaire de la petite rivière de la Baleine. La coulée est allongée dans l'axe de la vallée.

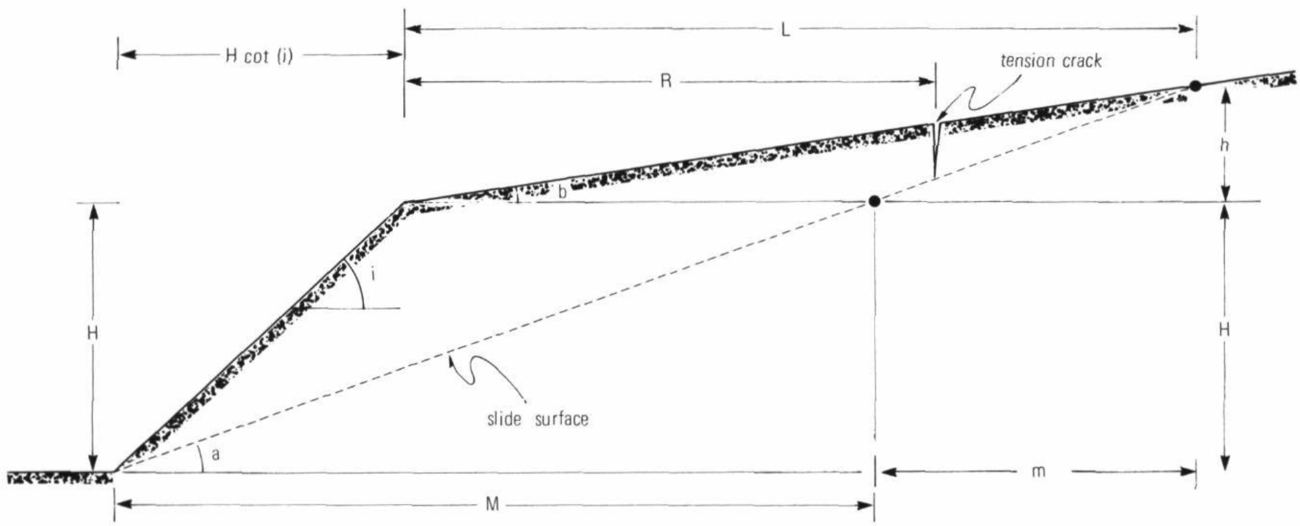
(1963) during earthquakes in 1960. These were also apparently considered to be non-retrogressive: the horst-graben topography of the craters seemed to be attributed to simultaneous subsidence of blocks of the top-stratum following structural collapse of thick underlying beds of saturated silt during the seismic activity. Moreover, there is no doubt that seismic vibrations have produced rib-type landslides in certain parts of Québec, for instance in the Charlevoix region (LAJOIE, 1981). However, the possibility of structural collapse throughout a great thickness of underlying material during seismic disturbances is quite different from normal flake slides: these develop along a thin failure zone or a distinct failure plane. Simultaneous subsidence (rather than retrogressive subsidence) appears much less likely in the latter case.

The possibility that some ribbed landslide craters were formed, not by retrogression, but by break-up of an initial flake slide mass must, nonetheless, be considered further. In a situation in which a flake slide does occur and then breaks up completely to produce a "retrogressive facsimile", clearly Equation 1 is irrelevant in predicting the penetration (R) of the slide area normal to the initial slope edge. In fact, in this case, it is the subsidence (dh) that would be the dependent variable in the equation.

It should be clear, however, that normal fiake slides require not only very low shear resistance along the failure plane, but also a significant dip in that plane towards the valley, at least if the driving force is to be big enough to produce movement of a long flake, and hence appreciable penetration into the slope. For example, the main Furre slide, a true intact flake slide mass (though followed by lateral retrogression: HUTCHINSON, 1961), with a relative penetration distance (R/H) of 8, required a quick clay seam dipping at 5°-7° towards the valley to permit failure. The Toulnustouc slide, described by CONLON (1966) as comparable with the Furre slide, and involving a relative penetration distance of 9, took place on a slide surface controlled by bedding planes of about 9°. This apparent dependence of flake slides on relatively steep stratigraphic bedding planes leads us to conclude that retrogressive facsimiles are probably relatively infrequent: situations in which post-glacial valleys, cut in marine sediments, display steep (> 5°) bedding towards the valley axis on *both* valley slopes are not common. And yet most valleys subject to ribbed slides do display scars on both sides of the valley: this is even true of the Baastad area (GREGERSEN and LOKEN, 1979, Fig. 3).

Moreover, the dependence of normal flake slides on relatively steep failure planes, whether or not they are stratigraphically controlled, must prevent the attainment of large penetration distance values: this follows from the simple geometry of the slide mass (Fig. 15). The maximum possible relative penetration distance (L/H) is given by

$$L/H = \frac{\cot(a) - \cot(i)}{1 - \tan(b).\cot(a)} \quad . \qquad (3)$$



$$(M+m)/(H+h) = (L + H.\cot(i))/(H+h) = \cot(a)$$

$$h = L.\tan(b)$$

hence ,

$$L/H = [\cot(a) - \cot(i)] \div [1 - \tan(b).\cot(a)]$$

FIGURE 15. Topographic constraints on the length (L) of a flake slide and hence on the relative penetration distance (R/H).

Contraintes topographiques sur la longueur (L) d'un glissement en bloc et, par le fait même, sur le rapport R/H.

which, with values of a = 5°, b = 2° and i = 25° (typical of Champlain Clay slopes) would yield a value of L/H equal to 15.5. This value decreases rapidly as (a) increases and (b) decreases. Moreover, given that the development of deep tension cracks would prevent full penetration of the flake into the slope (Fig. 15), actual values of penetration (R/H) will be significantly less than the maximum indicated by L/H above.

This important morphological constraint on the relative penetration distance of a flake slide would seem to preclude most of the slides listed in Table I from being genuine flake slides and hence retrogressive facsimiles. The slides at Baastad and Rigaud are exceptions to this statement. However, given the virtually identical morphology of these two slide scars with those of Saint-Ambroise (R/H = 15) and South Nation (R/H = 16), it would seem premature to conclude that the Baastad slide is a retrogressive facsimile, based solely on a "successful" back-calculation of the factor of safety using the flake slide approach. We acknowledge that flake slides do exist, and that some ribbed landslides may be retrogressive facsimiles, but these, we maintain, represent a small minority of earthflows in sensitive sediments.

DISCUSSION AND CONCLUSIONS

The article has attempted to demonstrate that, in valleys with floor widths of about 100 m, retrogression by spreading failure (involving mostly intact blocks of sediment), would, with complete translation of the spoil across the valley, result in relative retrogression distances (R/H) in the range 4 to 27. Such spreading failure would not require excessive liquefaction of the spoil, nor, therefore, extra-sensitive material.

A large number of recent landslides shows topographic features comparable with this type of flowslide; these include Sköttorp (1946), Hawkesbury (1955), South Nation River (1971), Baastad (1974), Saint-Ambroise-de-Kildare (1975), Rigaud (1978) and Havre-Saint-Pierre (1980). In addition, although the morphological features of older landslide scars are often very subdued, the data of MITCHELL and MARKELL (1974) and LAJOIE (1978) indicate that only a very small percentage of these older scars shows R/H outside the range which would be expected from simple spreading failure. The inference drawn is that the normal mode of failure in muddy sediments of medium sensitivity probably does not involve excessive liquefaction of the spoil.

Not all landslides attain full distances of retrogression allowed by the space for runout in the valley; numerous scars of small slides indicate this. Spatial changes in the ground material are an obvious reason for such premature halts to retrogression. The study of the 1979 Mabel slide (near Lachute) indicated an additional reason for this: retrogression may be aborted if no mechanism is available to move the initial slide block away from the food of the slope.

At the other extreme, it is clear that in some parts of Québec (*e.g.*, the Grondines region) and of Scandinavia, especially where the sediment is *both* soft and extra-sensitive, virtually complete liquefaction of the spoil may take place leading to excessive retrogression. Moreover, in some cases, it appears that excessive liquefaction of the spoil, and excess retrogression, are associated with bottleneck flowbowl plans, *e.g.* at Saint-Thuribe (1898) and at the Rupert River First Rapids (1970); but bottleneck flowbowls represent only a small percentage of retrogressive failures in sensitive sediments.

From a practical point of view, those slides which do involve virtually complete liquefaction pose much more serious threats than the normal type of failure. Because of the infrequency of the liquefaction type of slide mass, however, research, at least in Canada, has shown a strong bias towards the Petite Nation type of slide. It is perhaps now opportune to devote more time to this other form of retrogressive landslide: to the mechanics of clay liquefaction, to the reasons why some sediments are more susceptible than others, and to the geographic distribution of such deposits.

ACKNOWLEDGEMENTS

Fieldwork in the Lachute region was supported by the Geological Survey of Canada (MAC). Data from field vane tests at the Brownsburg site were provided by the courtesy of Jacques Lebuis, Service de la Géotechnique, Ministère de l'Énergie et des Ressources, Québec. Additional data for the Havre-Saint-Pierre slide were kindly provided by Daniel Paré, Ministère des Transports. We also acknowledge the criticism of earlier drafts by Jean-Yves Chagnon, Jacques Lebuis and François Tavenas without implying their acceptance of our views; and thank Abal Sen who drew the diagrams.

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