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**MEASURED MOVEMENTS OF CLAY SLOPES
IN THE OTTAWA AREA**

BY ANALYZED

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Measured Movements of Clay Slopes in the Ottawa Area

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Natural degradation of slopes is normally considered to involve surficial displacements resulting mainly from frost action, erosion, and downhill creep. Measurements from inclinometer installations in a variety of slope profiles in the Ottawa area show that significant deep-seated movements may occur in these slopes. These movements are associated with seasonal peaks in ground water pressures within the slope and may contribute to the long term degradation of the slope.

While the factor of safety against catastrophic failure of a slope is of prime importance, the possible effects of deep-seated slope movements should not be disregarded when considering adjacent land use.

On considère généralement la dégradation des pentes comme le résultat de déplacements superficiels causés surtout par l'action du gel, de l'érosion, et de glissements (creep) vers le bas des pentes. Des mesures effectuées à l'aide d'inclinomètres installés sur des pentes à profils variés, dans la région d'Ottawa, démontrent que d'importants déplacements localisés en profondeur peuvent se produire sur ces pentes. Ces déplacements sont associés aux maxima saisonniers de la pression de l'eau souterraine et peuvent, à long terme, contribuer à la dégradation des pentes.

Lorsque le facteur de sécurité contre la rupture soudaine d'une pente est de première importance, les effets possibles des mouvements en profondeur sur cette pente ne doivent pas être négligés lorsqu'on projette l'utilisation des terrains adjacents.

Introduction

Unstable slopes are common in the Champlain Sea clay terraces of the Ottawa Valley region. Many recent landslides can be identified on air photographs taken along the Ottawa River and its tributaries. Landslides are often associated with erosion at the toe of the slope, and the air photographs indicate that these instabilities are a primary mechanism in creek valley widening; debris from a landslide pushes the creek against the opposite valley wall where toe erosion can initiate a new landslide. This process is illustrated in Figs. 9, 10, and 11.

The predominant clay (commonly referred to as Leda clay) in the Ottawa area is of marine origin but has been reworked and redeposited in a fresh water environment (Gadd 1962). The work of Crawford and Eden (1967) indicated that slopes composed of this clay would

not be susceptible to landslides if the high strengths measured in laboratory tests could be mobilized. Extended laboratory testing together with re-analysis of several landslides by Eden and Mitchell (1970) showed that slope stability is dependent on the local transient ground water pressures and is not related to the high strength (presumed due to natural cementation) that is exhibited by the clays when tested under confining stresses in excess of 1 kg/cm². A decrease in strength under lower confining stresses is attributed to inherent closely spaced planes of weakness in the clay.

In addition to the above developments, Mitchell (1970) showed tests on clay from one site in the Green Creek Valley in which the high (cementation) strength was mobilized even when the specimens were unconfined at failure. Sangrey and Paul (1971) carried out some detailed studies in this valley and confirmed earlier identification, by Gadd (1962), of two distinctly different outcropping clay layers in the valley walls. They suggest that the lower,

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FIG. 1. Map showing general locations of inclinometers.

less fissured, marine clay can be identified by a high ratio of sodium to calcium ions in the pore water. The closely fissured reworked clays have a relatively high concentration of calcium ions. As part of a study of the mechanics of observed landslides, six S.G.I. type inclinometers (Kallstenius and Bergau 1961) were installed in slopes in the Ottawa area. Three years of slope movement observations from these installations are presented in this paper.

Inclinometer Locations, Installations, and Measurements

The inclinometer installations were made in slopes at three locations: the south bank of the Ottawa River near Rockcliffe Air Base, the Green Creek Valley near the eastern boundary of Ottawa city limits, and the Breckenridge Creek Valley about 15 mi (24 km) northwest of Ottawa. Figure 1 shows the general locations of these installations, and Fig. 2 indicates their designation and their location with respect to recent landslides. The six installations are listed in Table 1 together with references to the landslides shown in Fig. 2. Some basic information on the installations and adjacent landslides is also contained in Table 1.

The inclinometer tubes, 1.5 in. (3.81 cm) I.D. $\times$ 1.75 in. (4.34 cm) O.D. semi-rigid P.V.C. (schedule A) pipe, were pushed into holes hand-augered with a 2 in. (5 cm) diameter auger bit. The bottom end of each tube was sealed with a conical tip of 2 in. (5 cm) outside diameter. A special pushing apparatus was developed to overcome the friction without bending or crushing the tube. Inclinometer tubes were placed in the lower half of the slope where a reasonably convenient spot to auger a vertical hole could be found. Tube lengths of 10 m were normally used so that the bottom end extended below the elevation at the toe of the slope. Thus it was thought that any deep-seated movement occurring in the slope could be detected.

The initial inclination of each tube was measured at 2 ft (0.6 m) intervals in the pipe several months after installation. Subsequent measurements were taken after each seasonal (spring and autumn) peak in ground water levels with occasional intermediate measurements. Movements were calculated from the change in inclination of each tube using the bottom of the tube as datum. Movements calculated over a 10 m tube length are considered to be accurate to ± 0.05 cm.

FIG. 2. Detailed locations of inclinometers.

Presentation of Measurements

It may be noted from Table 1 that the first three inclinometers listed (R1, G1, B1) were installed in slopes that were similar to adjacent ones where recent landslides had occurred. Furthermore, these slopes were chosen because they were typical of slopes in their immediate vicinity. The sites of the other three installations (R2, G2, B2), instead of being in typical natural slopes, were chosen because particular environmental factors were prevalent. Measurements of slope movements are presented below

for each installation in the order listed in Table 1. In each case a figure showing the slope profile and the inclinometer installation drawn to scale is presented. Measured movements are plotted on the same figure. It should be noted that the scales of these plotted movements are not the same in all figures. It should further be noted that the semi-rigid inclinometer tube is not considered sufficiently flexible to measure the near-surface movements due to solifluction (as recorded, for example, by Williams 1966) and measurements shallower than 1 m are therefore not recorded. All movements were

TABLE 1. Information on inclinometer installations and adjacent landslides

Inclinometer installations			Adjacent recent landslides		
Location and designation	General slope description	Slope height and aver. angle	Slope height and aver. angle	Date, type, and size of landslide	Reference
Rockcliffe R1	Natural slope, typical of this section of the bank	14 m 26°	13 m 28°	1969 retrogressive toe failure 8000 yd ³	Paul 1970
Green creek G1	Natural slope, typical but without toe erosion	19 m 28°	20 m 26°	1971 retrogressive toe failure 8000 yd ³	Unpublished
Breckenridge B1	Natural slope with toe loading from spoil of recent landslide	29 m 27°	28 m 25°	1963 retrogressive toe failure 30 000 yd ³	Crawford and Edén 1967
Rockcliffe R2	Graded (flattened) natural slope	13 m 20°	13 m 28°	1967 retrogressive toe failure 30 000 yd ³	Edén and Mitchell 1970
Green Creek G2	Steep natural slope with outcropping marine clay	15 m 35°	19 m 26°	1967 2000 yd ³ slide in upper 13 m of slope	Mitchell 1970
Breckenridge B2	Natural slope subjected to unusually rapid erosion	28.5 m 22°	28 m 25°	1963 retrogressive toe failure 30 000 yd ³	Crawford and Edén 1967

downslope as indicated in Figs. 3–8 and are listed in Table 2.

Figure 3 shows the slope profile and position of inclinometer R1. This slope is typical of over a mile of the Ottawa River bank in the Rockcliffe area of Ottawa and is situated between two recently documented landslides (see Table 1 and Fig. 2). The total slope movements for a period of nearly 2.5 years and the movement during one year are plotted in Fig. 3. Readings taken in May 1969 indicate that most of the annual movement develops during the spring breakup when the ground water levels are high. In this slope the movements average about 0.25 cm per year and the maximum movement is at an elevation corresponding to the toe of the slope. Although no tension cracks have been observed at the top of this slope, tension cracks have developed in the paved surface of parking areas at the top of similar slopes located between inclinometer R1 and the landslide reported by Paul (1970) and noted in Table 1. These tension cracks are a positive indication of slope movements.

Figure 4 shows the slope profile and the position of the inclinometer G1. This slope is about 200 m downstream from the landslide noted in Fig. 2 and Table 1. A photograph of this landslide is presented in Fig. 9. The major difference between this slope and the slope

where the landslide occurred is that Green Creek, in its meanderings, was eroding the toe of the slope that failed. In June 1968 Mr. G. Munro, occupant of the land where these slopes are located, showed the authors a tension crack at the location of the backscarp of the landslide shown in Fig. 9 which occurred 3 years later. At that time a vertical displacement of several centimeters existed at the tension crack, and an attempt was made to put an inclinometer in this slope rather than the slope where G1 was installed. The slope that failed was, however, thickly covered by small cedars and it was not possible to install the inclinometer in a suitable place.

A large percentage of the total slope movement plotted in Fig. 4 developed between October 1970 and August 1971. It is unfortunate that no measurements were made immediately following the spring season in 1971, but it is believed that most of this movement occurred during the spring when ground water pressures were high. The water levels in this area were exceptionally high during March 1971 due to the above-normal precipitation. The maximum movement is, again, close to the elevation of the toe of the slope.

The information presented in Fig. 5 refers to a natural slope immediately downstream from the 1963 Breckenridge landslide noted in Table

FIG. 3. Measured movement in a natural slope, Ottawa River.

TABLE 2. Summary of slope movement measurements

Inclinometer No.	Location	Maximum rate of movement/month (approximate), cm	Time of max. movement	Average (3 years) movement cm/year	Depth of maximum movement	Remarks
R1	Rockcliffe Ottawa R.	0.2	Spring	0.25	Toe elevation of slope	Typical natural slope with some toe erosion
G1	Green Creek Valley	0.3	Spring	0.11	Toe elevation of slope	Natural slope without toe erosion
B1	Breckenridge Creek	0.6	Spring	Not known	Not known	Shallow inclinometer toe stabilization from former landslide
R2	Rockcliffe Ottawa R.	6.0	Following slope grading	1.3	Ground surface	Graded fill on natural slope
G2	Green Creek Valley	0.2	Spring	0.27	Ground surface	Movement in fissured clay overlying stiff marine clay
B2	Breckenridge Creek	4.0	Autumn	Slope failed	Toe elevation of slope	Rapid toe erosion

1. The tube-pushing apparatus was not available for this first installation (May 1968) and a maximum depth of 6 m instead of the initially intended 10 m was attained. The movements plotted in Fig. 5 are difficult to interpret, since the movements between September 1968 and

May 1969 are larger than the total movements to August 1971. The explanation of this apparent anomaly follows.

All measurements prior to August 1971 showed the pattern of maximum movement at the surface decreasing with depth, as with other

FIG. 4. Measured movement in a natural slope, Green Creek.

FIG. 5. Measured movement in a natural slope, Breckenridge Creek.

sites. In the spring of 1971, tension cracks appeared in the slope above the inclinometer installation. These cracks indicated that a deep-seated movement had developed and caused the reverse tilting of the inclinometer tube. Since movements are calculated from measured

changes in inclination of the tube from bottom to top, it is apparent that the movement in this case is taking place below a depth of 6 m and the bottom of the tube is not a fixed datum.

The slope in which inclinometer R2 was installed is located directly adjacent to the 1967

FIG. 6. Measured movement in a graded slope, Ottawa River.

Rockcliffe slide noted in Table 1 and in Fig. 2. Concern for the safety of a hangar located at the top of this slope led to a decision to grade the slope, and the inclinometer was installed two months after these grading operations. Figure 6 shows the original slope profile, the graded slope profile, the inclinometer tube, and the measured movements. The movements indicate that the overall slope stabilization has been successful, but that the fill material is moving relative to the underlying original material. Movements that developed during the first two months after measurements began represent about one-third of the total movement after three years. Movements between October 1970 and August 1971 were found to be quite small (within the accuracy of the instrument). These data suggest that deep-seated movement can be prevented by increasing the factor of safety of a slope. It also indicates that buried services, installed in graded natural slopes, may be subjected to stresses from soil movement.

Figure 7 shows the movements measured in an inclinometer installed in a steep slope composed of two clays. The lower clay has a high ratio of sodium to calcium ions in the pore water, while the upper clay has a high ratio of calcium to sodium ions in the pore water (Sangrey and Paul 1971). The boundary between

these two clays is indicated in Fig. 7 and corresponds with the base elevation of a landslide which occurred in the adjacent slope (see Fig. 2 and Table 1). The upper clay is closely fissured (these fissures become apparent when a block of this clay is broken up), while the lower clay appears to be more intact (Mitchell 1970; Sangrey and Paul 1971). Only the total movements developing over a three-year period are plotted in Fig. 7. Measurements indicate that the upper clay is moving at about 0.25 cm per year maximum but the lower clay shows no movement. All of the other slopes instrumented are composed of clay of similar nature and origin to the upper clay in this slope. Eden and Mitchell (1970) have shown that the fissured clays exhibit relatively large strains prior to failure in triaxial tests. The lower marine clay at this location exhibits a brittle type of failure. The data in Fig. 7 support the concept regarding the differences in stress-strain behavior of the two clays and indicate that slope movements might occur only in the fresh water redeposited clays.

After the 1963 Breckenridge slide (Fig. 2) the creek was dammed with debris and forced to cut a channel at the toe of the opposite slope. Inclinometer B2 was installed in this slope in August 1968 when the creek had eroded an

FIG. 7. Measured movement in a steep natural slope with outcropping marine clay, Green Creek.

almost vertical face about 4 m high at the base of the slope. By October 10, 1968, this face had undergone considerable surficial sloughing and a tension crack had formed about 3 m downslope from the inclinometer tube. The displacements plotted in Fig. 8 were measured on November 12, 1968. At this time a second tension crack had formed about 1 m away from the inclinometer tube. These cracks appeared to extend to about 1 or 2 m depth and were about 2 cm wide at the top. By March 27, 1969, a small landslide extending about 6 m above the inclinometer location had sheared the inclinometer tube and removed the upper half of this installation. By April 25, 1969, a larger landslide about 70 m long by 30 m wide had developed at this site along with another smaller slide on the downstream side. Figures 10 and 11 show the development of these landslides. The larger slide had a failure plane at about 3.5 m depth almost parallel to the original ground surface and extending to within 20 m of the pole structure at the top of the slope. Water was seeping out at the backscarp about 0.5 m below ground level on April 25. The profile of this slope and the failure planes

of the landslides discussed above are shown in Fig. 8.

The movement of 0.8 cm measured by the inclinometer occurred during the late autumn months when the ground water levels normally show a small seasonal peak. Larger movements downslope of the inclinometer are indicated by the formation of tension cracks. These movements are associated with the removal of toe support by erosion and the maximum movement corresponds, in elevation, to the eventual failure surface. It is interesting to note that, despite these large movements, the landslide did not develop until the following spring when the ground water levels were at or near their seasonal maximum.

Discussion of Measurements

To investigate the influence of changes in ground water level on deformation in the slopes a sample of clay from the Rockcliffe area (from 10 m depth) was placed in a triaxial cell equipped with a rotating bushing to reduce piston friction. A normal drained compression test was carried out using incremental loads until the sample was at equilibrium under ap-

FIG. 8. Measured movement in a slope subjected to rapid erosion, Breckenridge Creek.

proximately 90% of its failure load. At this stage the pore water pressure in the sample was increased by 0.05 kg/cm^2 by increasing the back pressure from 1.00 kg/cm^2 to 1.05 kg/cm^2 . This would be equivalent to a rise in ground water level of 0.5 m . The small increase in pore water pressure caused the sample, nominally 8 cm high by 10 cm^2 in cross-sectional area, to undergo an axial deformation of about 0.4 mm in 1 min . After 1 min the back pressure was decreased to 1.00 kg/cm^2 , establishing the earlier equilibrium stresses, and the sample deformation decreased such that no axial deformation was observed during a 2-min period. This procedure was repeated with varying time intervals up to 4 min . After several cycles the sample had undergone about 3.5% axial strain without failure, and equilibrium was again established under the back pressure of 1.0 kg/cm^2 . This test supports the concept that slope movements are associated with seasonal high ground water levels.

While the data presented cover a period of only three years, there is no indication that these are not continuing conditions. Maximum movements observed in a typical natural slope are in the order of 0.25 cm per year. Maximum movement occurs at an elevation corresponding to the toe of the slope and to the depth of the

most critical failure circle. Maximum rates of movement appear to correlate with periods of high ground water levels. Deep-seated slope movements could theoretically lead to either the formation of tension cracks and subsequent landsliding or, if the slope does not fail, eventual degradation and stabilization. The latter possibility derives from considerations of continuity; if the toe of a slope moves outwards and no tension cracks develop, a downward movement of the upper part of the slope and a general decrease in slope angle must occur. It might be noted that many of the stable natural slopes in the study areas have a profile characteristic of outward toe movement (toe bulging) and decrease in slope angle towards the uplands. The profile in Fig. 4 could be considered an example of such movements. Field observations suggest that the appearance of tension cracks is indicative of a potentially dangerous slope. Eden and Mitchell (1970) suggested that tension cracks play a direct role in accelerating movements that lead to landslides by providing access for surface water into the shear zone. These authors also showed that there is little post-peak decrease in shearing resistance in laboratory specimens of these clays when tested under the stresses applicable to the landslide problems, a necessary condition if a slope is

FIG. 9. Landslide in Green Creek Valley, 1971.

to be considered stable following large deep-seated movements.

The effects on slope movements of slope flattening, of rapid erosion, and of an outcropping of underlying stiff marine clay have been investigated. Changes in slope geometry (by

flattening or by erosion) appear to be determining factors in the rate and depth (or form) of slope movements. The 1969 Breckenridge landslide (that removed inclinometer B2) and subsequent regression resulted in a failure plane that was almost parallel to the original ground

FIG. 10. Breckenridge landslides, March 27, 1969. (a) Taken from helicopter. (b) Taken from 1963 landslide crater.

surface. This infinite-slope type of sliding (as opposed to the usual circular arc slide) is considered to be related to the form of the slope movements resulting from the fairly rapid removal of the toe material.

Conclusions

A summary of the measured slope movements is included in Table 2, and the following conclusions are drawn from this study:

FIG. 11. Breckenridge slides, April 25, 1969. (a) Taken from 1963 landslide crater. (b) Closer view of larger slide.

1. Relatively deep-seated movements do develop in some of the natural slopes in the Ottawa area. These movements appear to occur during periods of high ground water levels.
2. Large slope movements and landslides of the infinite slope type (failure plane almost parallel to the ground surface) may occur in the 'fissured' clays if toe erosion (or excavation) is extensive.
3. While flattening of natural slopes leads to an increased overall stability, movements are likely to develop at the interface between the fill material and the original ground surface. Care should be taken to insure the integrity of services placed in natural slopes and, in particular, in flattened natural slopes.
4. Movements measured in inclinometer G2 would tend to support the concept of two clay layers, which exhibit different stress-strain properties, outcropping at this location in the Green Creek Valley.
5. Long-term, deep-seated, slope movements may contribute to apparent degradation of slopes in which landsliding does not develop.

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