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Publisher's version / Version de l'éditeur:
https://doi.org/10.1139/t64-004
Canadian Geotechnical Journal, 1, 2, pp. 104-114, 1964-03

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by

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Reprinted from
CANADIAN GEOTECHNICAL JOURNAL
Vol. I, No. 2, March 1964
pp. 104–14

RESEARCH PAPER NO. 211
OF THE
DIVISION OF BUILDING RESEARCH

Price 25 cents

Ottawa
March 1964

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EARTHFLOWS AT THE BEATTIE MINE QUEBEC, CANADA*

W. J. EDEN†

SYNOPSIS

In June 1943 an earthflow involving more than one million cubic yards of varved clay occurred at the Beattie Mine. Subsequent remedial measures resulted in further large landslides. This paper describes the soil conditions, the sequence of events, and attempts to assess the stability of the clay slopes. It was found that the undrained analysis led to an unsafe assessment but that Terzaghi's rule for critical heights of slope gave a better indication of stability.

SOMMAIRE

En juin 1943, un glissement de terrain d'au déla d'un million de verges carrées d'argile stratifiée survint à la mine Beattie, Province de Québec. Les mésures de protection qui furent prises par la suite entrainèrent cependant d'autres éboulis. Cette communication décrit les conditions du sol, la suite des évènements, et des tentatives pour évaluer la stabilité de ces talus d'argile. Les résultats indiquent qu'une analyse fondée sur des essais non drainés conduit à une appréciation dangereuse, alors que la loi de Terzaghi, en rapport à la hauteur critique des talus, donne une meilleure indication de la stabilité.

The Beattie Mine is located in north-western Quebec at the village of Duparquet, about fifteen miles south of Lake Abitibi, in a clay plain resulting from the accumulation of varved clay deposited in glacial Lake Barlow-Ojibway. An open pit or "glory-hole" was gradually enlarged in the course of mining operations so that larger and larger amounts of varved clay were stripped away from the perimeter of the pit. In June 1943 a rockfall triggered a landslide in the clay slopes that developed into an earthflow involving more than one million cubic yards. Attempts to rehabilitate the mine resulted in further serious landslides in 1945 and 1946. This paper is a case record of the disaster, with emphasis on the performance of the varved clay. The performance of the clay slopes is compared with results of soil tests conducted in 1960 and 1961.

HISTORY OF THE MINE

The Beattie Mine began production in 1933 with gold-bearing ore won from a large, relatively low-grade ore body lying along the north flank of a rock ridge oriented in an east–west direction. Approximately 200 yards north of this ridge, another ridge, formed of glacial till, defined the intervening valley, which was filled with varved clay underlain by sand.

At its west end the ore body outcropped on the surface, plunging under the overburden towards the east. Ore was mined by a combination of glory-hole and underground stoping methods. The glory-hole was an open pit with very steep sides and sloping ends; a hanging wall was supported on a footwall by four rock pillars across the pit. The ends of the pit sloped at about 40 degrees. Here, the ore was mined and rolled down the slope to an underground opening in the pit bottom. Production was scheduled so that the glory-hole was worked

*Presented at 17th Canadian Soil Mechanics Conference, Sept. 12, 1963, Ottawa.
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during the summer months and the more expensive underground mining was conducted during the winter.

Figure 1 is an aerial view of the mine taken in 1938 and shows the pit with its system of pillars. By 1943 the glory-hole was about 1000 ft. long, 40 ft. wide at the east end, and over 200 ft. at the west. At its deepest point the pit was about 300 ft. below the surface.

FIGURE 1. Aerial view of Beattie Mine, 1938 (courtesy of Beattie-Duquesne Mines Limited)

As production proceeded the pit was gradually lengthened, requiring the stripping of greater and greater depths of overburden from the north side and east end. In the early stages the stripping was accomplished by horse-drawn scrapers, but as the amounts of stripping grew larger a tower dragline system and mechanical excavating equipment were used. In each case the stripped material was deposited near the top of slopes cut in the overburden at 4:1, a fairly wide berm bordered the pit. Figure 2 illustrates the clay slopes as they were in 1943. A pump barge, shown in the photograph, controlled seepage water. The maximum depth of overburden excavated by 1943 was approximately 100 ft., and consisted of 85 ft. of varved clay overlying 15 ft. of sand or till.

The varved clay was deposited in glacial Lake Barlow-Ojibway (Antevs, 1925) and was found later to be nearly normally consolidated. The clay occupied a narrow valley north of the ore body and extended westward about one mile to the shores of Lake Duparquet. At its lowest point the rock rim of the pit was about 60 ft. below the level of Lake Duparquet (elevation 885).

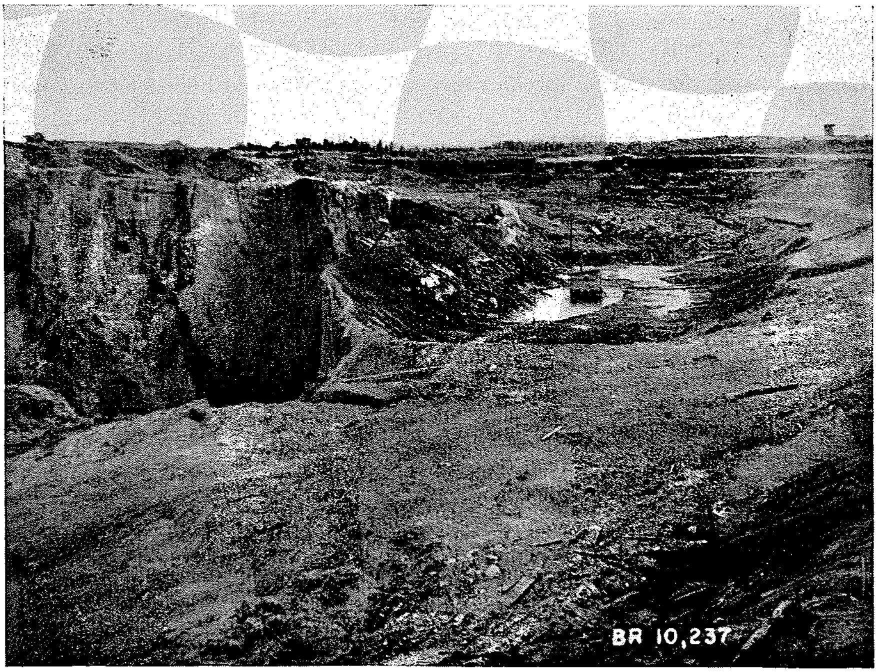

FIGURE 2. Clay slopes, 15 June 1943 (courtesy of Mr. F. E. Patton)

Seismic surveys conducted about 1946 have shown that there was no ledge of bedrock to impede seepage between the rim of the pit and the lake. Near the west end of the pit there was a tailings disposal area flooding the low-lying ground west of the mine. Records indicate considerable seepage through the sand, particularly at the west end of the pit.

The Earthflows

The first difficulties with the clay slopes were recorded in 1937. On 19 June a landslide occurred on the north-east corner of the glory-hole. As shown on Figure 3, it had the characteristic shape of an earthflow and involved a few thousand yards of clay. The second recorded slide occurred in 1942, mid-way along the north side of the pit. Like the previous slide it was relatively small and did not seriously affect operations in the mine.

On the night of 15 June 1943, however, a very large earthflow involving more than one million cu. yd. occurred. The glory-hole was completely filled, and owing to the fluidity of the clay many of the underground workings were penetrated. Some of the clay ran nearly half a mile along the sixth level drift towards the neighbouring Donchester Mine, which was connected to the Beattie Mine on this level. The immediate cause of the landslide appears to have been the collapse of a main pillar in the pit; this caused a rockfall on the north side and, in turn, initiated the earthflow. As indicated on Figure 3 the landslide involved a large area of clay north and east of the pit. Borings made in 1960 and 1961 indicate that nearly all the clay in this area of the pit was removed by the earthflow.

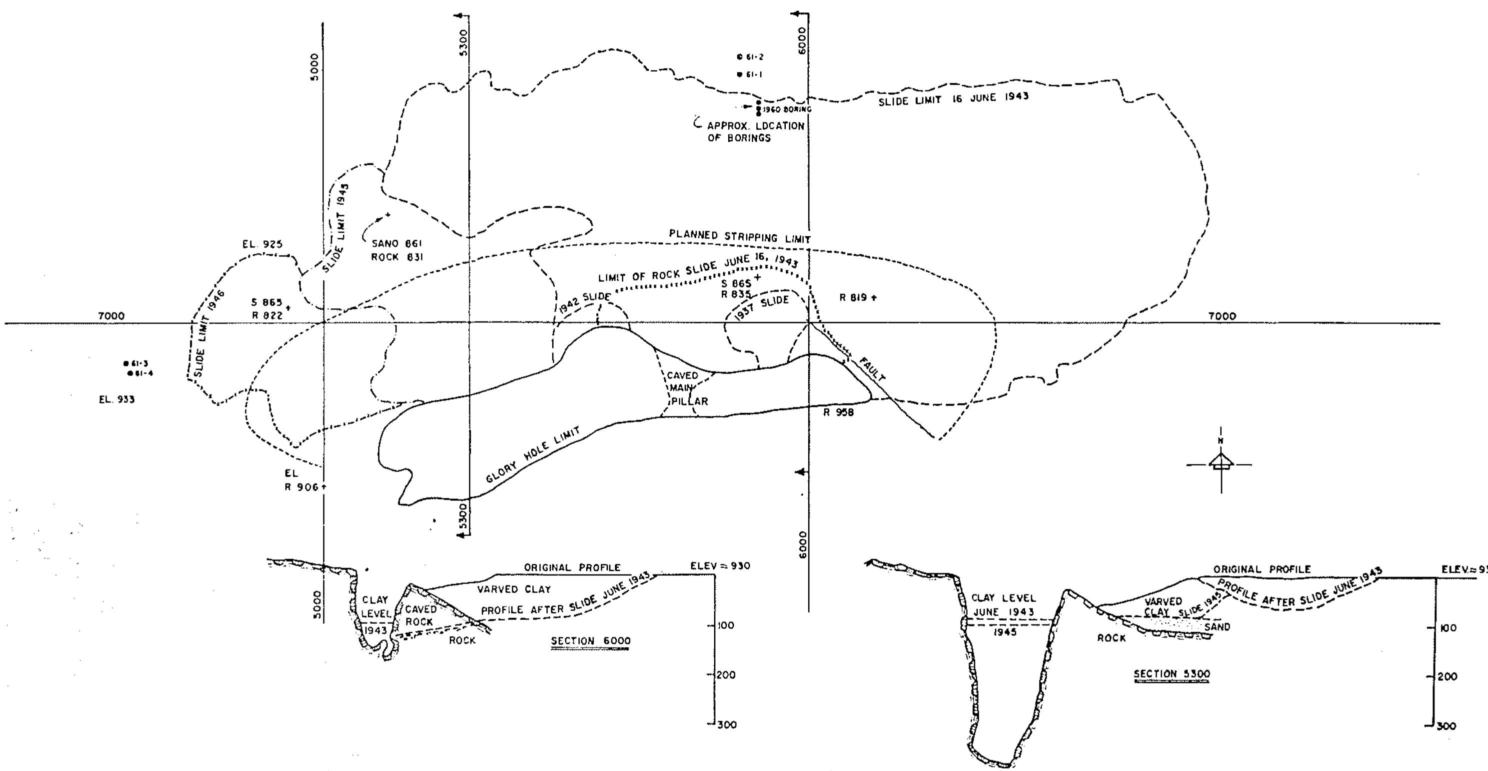

FIGURE 3. Plan of Beattie Mine showing location of earthflows

The neighbouring Donchester Mine (under the same management as the Beattie Mine) remained in operation while steps were taken towards the rehabilitation of the Beattie Mine. In the underground workings the clay was sluiced with high pressure water jets and the resulting slurry pumped to the surface. Small hydraulic dredges were set up in the glory-hole and crater to remove clay from the working area. By June 1946 about $1\frac{1}{2}$ million cubic yards had been removed from the pit. It was estimated that a further one million cubic yards would have to be removed before production could be resumed.

During 1945 further landslides occurred at the west end of the crater, undoing some of the work of the dredges. These continued into 1946, the largest, on 25 June 1946, involving about 250,000 cubic yards. Figure 4 shows photographs taken in July 1946 that illustrate the landslides. From information obtained from the former mine engineer, it appears that the slides at the

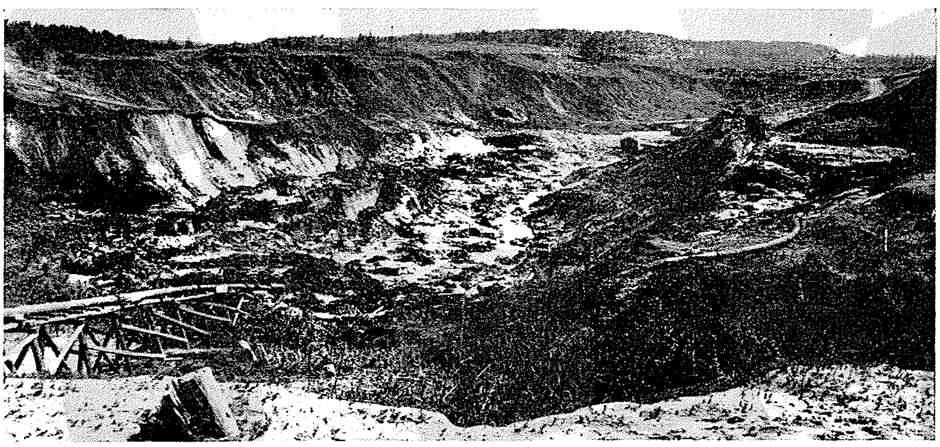

FIGURE 4. View of Mine from west end showing recent landslides, July 1946 (courtesy of Mr. F. E. Patton)

west end were rather shallow, involving perhaps the top 20 to 25 ft. of the clay. The first evidence of a slide would be a tension crack; two or three days later a sudden movement would occur, causing the clay to liquefy and flow rapidly towards the dredges located several hundred feet to the east. Observers could not associate the occurrence of the slides directly with the operations of the dredges. Slides continued, however, until September 1946 when dredging work was suspended.

In the fall of 1946 a decline in the price of gold brought an end to large-scale operations at the Beattie Mine. From 1946 to 1956 the pit area was kept free of water, and a shallow shaft was sunk at the west end to reach a lode of comparatively rich ore. Since 1956 no further work has been done, and the pit area has been allowed to flood from local drainage. Figure 5 is a photograph illustrating the area in May 1960. This view is approximately the same as that in Figure 4. The shores of the lake that can be seen are the scarps left

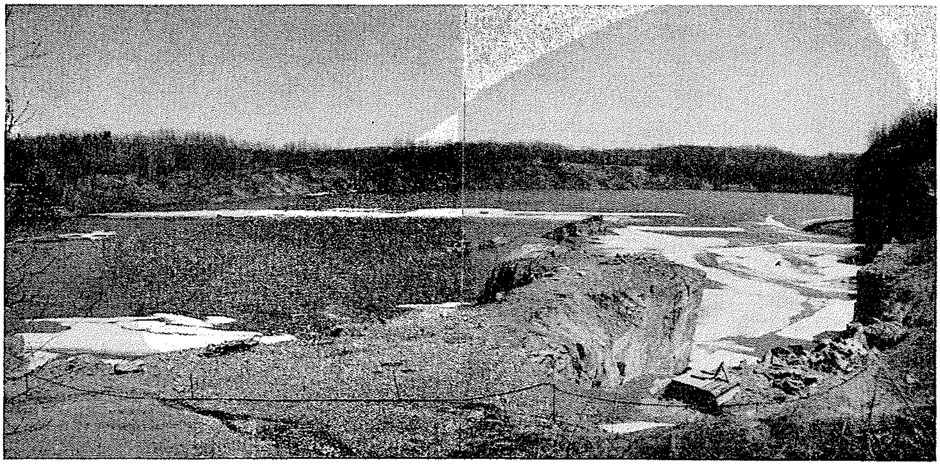

FIGURE 5. View of Mine from west end, May 1960

by the landslides; the rock wall at the right is the former footwall of the pit and the rock point jutting out of the water is the top of the hanging wall.

SOIL INVESTIGATIONS

During 1960 and 1961 field work consisted of taking a number of borings and conducting surveys. All active mining work had ceased in both the Donchester and the Beattie Mine, and access to the area was rather difficult; because of the flooding of the pit area it was not possible to locate the borings ideally. They were made midway along the north side of the crater and at the west end (Figure 3). From visual inspection and from the results of the borings on the north side it was thought that most of the clay north and east of the mine had been removed by the landslides. Only at the west end was there an appreciable depth of clay remaining, and it was here that most of the detailed investigation was concentrated. A series of low-level vertical aerial photographs had been taken of the mine area during July 1945. From these it was possible to make a reasonably accurate contour map of the west end of the pit. Many of the mine plans showed contours of the slopes at various stages.

In general, the sequence of the soil strata consists of from 0 to 15 ft. of silty sand on the surface, a horizon of varved clay up to 80 ft. thick, and then a sandy stratum underlain by bedrock or glacial till on the north side. Borings 61–3 and 61–4 were located at the west end of the crater, and the logs from these borings are presented in Figure 6. Field vane tests were conducted at 1 ft. intervals in the clay. In hole 61-3 thin-walled tube samples were taken with the NGI-type fixed-piston sampler.

In Figure 6, the boring log shows that the top 15 ft. consist of silty sand—very loose material that was easily penetrated by the drill casing. The varved clay stratum extends from 15 to 55 ft. Near the top of it the dark layers are thicker than the light layers, although both may be considered clay

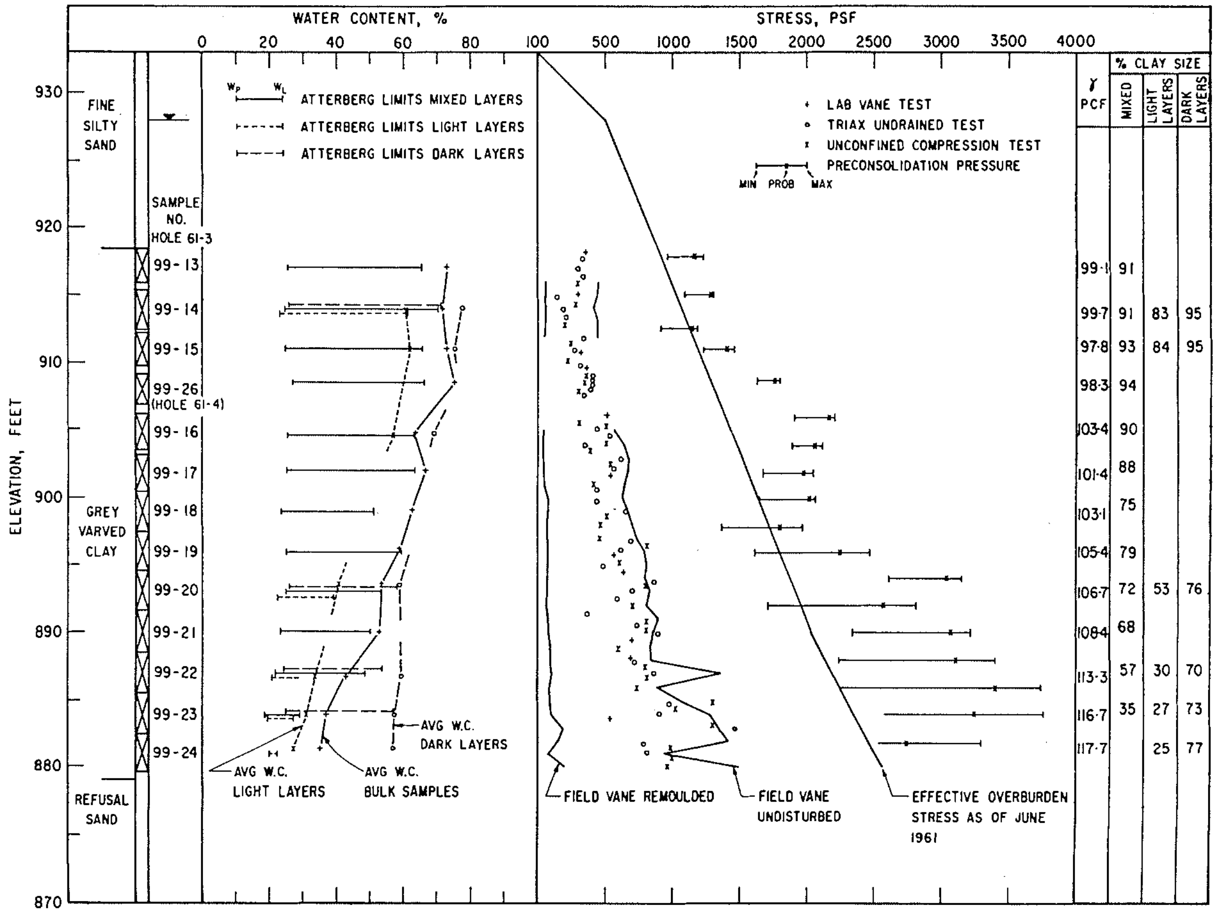

FIGURE 6. Boring log showing test results

materials. With increase in depth the ratio of dark to light layer changes, until at the bottom of the clay the light layers are thicker than the dark layers and consist of sandy silt. The dark layers continue to be clayey with reduced plasticity; the water content profile shows this tendency.

The undrained shear strength increases with depth, with the apparent c/p ratio remaining nearly constant. Field vane strengths range from about 400 lb./sq. ft. at an elevation of 915 to 1000 lb./sq. ft. at an elevation of 880. The apparent c/p ratio is about 0.4, this value being partially attributable to an overconsolidation process. The consolidation test results indicate that the clay has been affected by the mine drainage system. It is postulated that this drainage caused a full draw-down and the initially normally consolidated clay tended to be consolidated by the full overburden pressure.

A series of undrained triaxial and unconfined compression tests was conducted on the tube samples. These undrained strengths were appreciably less than those indicated by the field vane test. These results confirm that disturbance is a serious factor in sampling varved clays, as shown in a previous investigation (Eden and Bozozuk, 1962).

Consolidated undrained (CU) triaxial tests were conducted on a number of specimens. A change in the shear characteristics of the material is indicated as occurring at an elevation of about 890, the material below this elevation having an angle of shearing resistance ϕ' of about 28 degrees and that above it about 22 degrees. Results of the tests on the upper clay are presented in Figure 7, which is a Mohr diagram showing the effective stress circles at the maximum deviator stress obtained during the test. All these tests were conducted at consolidating pressures greater than the preconsolidation pressure of the samples. The average c/p measured was 0.29.

In summary, it appears that initially the varved clay was almost normally consolidated. Owing to the drainage works, the clay has been partially consolidated under full overburden pressure. Hence, the undrained strengths

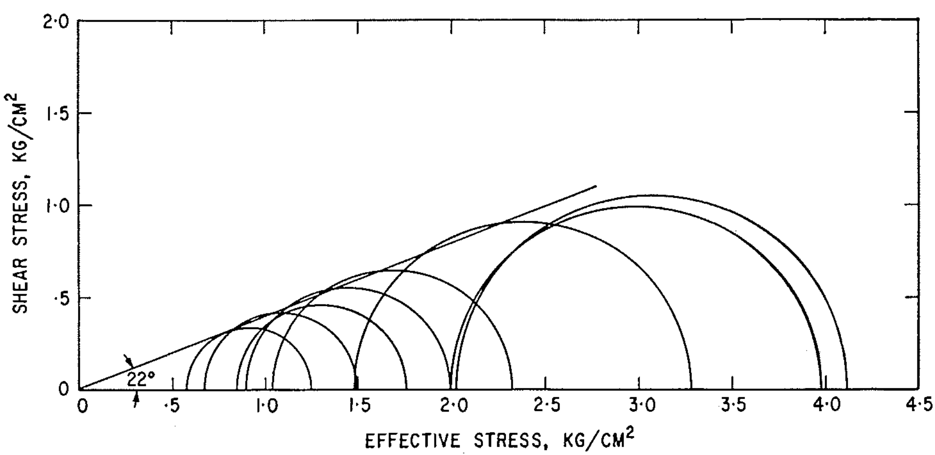

FIGURE 7. Mohr diagram of triaxial test results on upper clay

measured with the field vane are probably higher than those existing at the time of the landslides. This effect will be greater with depth.

Stability of the Slopes

Information concerning the slopes prior to 1943 is lacking in the detail necessary to conduct a stability analysis. It is interesting to note, however, that if the slopes were cut to 4:1 as planned, they would be critical according to the analysis proposed by Gibson and Morgenstern (1962) and using the c/p measured in the triaxial test. It is thought that the clay would have been nearly normally consolidated at that stage. On the other hand, the stripping was carried out rather slowly, allowing the slopes to drain to a certain extent as construction proceeded.

Using the aerial photographs taken in June or July 1945, it was possible to obtain reasonably reliable slope profiles for the west end of the mine where slope failures were occurring. The steepest profile obtained is shown on Figure 8. Both total stress and effective stress analyses were attempted on this profile.

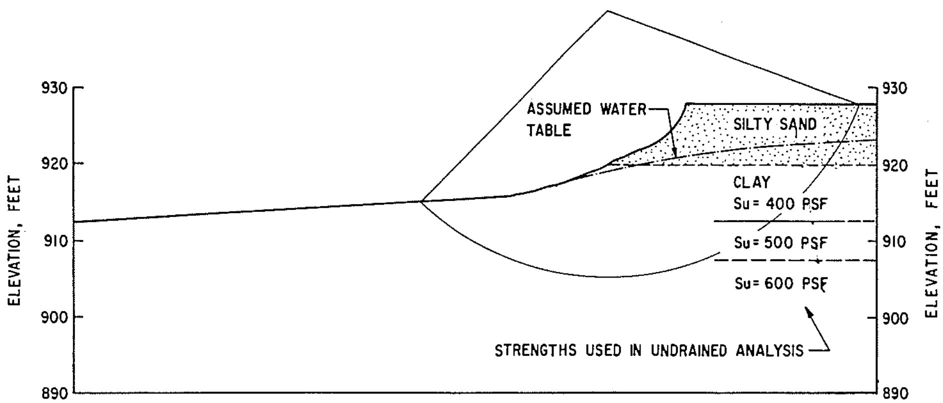

FIGURE 8. Profile X—X at west end

For the undrained analysis several shallow circles were tried using shear strengths of 400, 500, and 600 lb./sq. ft. according to the depth of the circle and the measured field vane strengths at corresponding elevations. No strength was assigned to the silty sand stratum on the surface. Although the strengths measured with the vane in 1961 were considered to be slightly higher than the strengths at the time of the landslide because of consolidation, this analysis might be expected to give a reasonable indication of potential instability. However, the minimum safety factor obtained was 2, and the analysis cannot therefore be considered satisfactory. The large discrepancy between the calculation and the observed behaviour of the clay cannot be accounted for by the consolidation effect alone.

The situation at the Beattie Mine can be compared with the varved clay slopes at Steep Rock Iron Mine (Legget, 1958) where 22 ft. high slopes at 3:1

frequently failed under rapid drawdown conditions although the average shear strength was 550 lb./sq. ft. The undrained analysis of these slopes yields a safety factor of 1.7. At Steep Rock, Sutherland (1959), found that Terzaghi's (1948) rule for a critical height of slope against failure by spreading could be applied to the Steep Rock slopes. This rule, $Hc = 4c/\gamma$, is based on the assumption that excess pore water pressure is developed in the clay along a horizontal plane sufficient to overcome the undrained strength. At Steep Rock, the undrained strength was 550 lb./sq. ft. and the critical height was 22 feet. At the Beattie Mine, the height of the slope shown in Figure 8 was about 16 feet, which is in agreement with the undrained strength of 400 lb./sq. ft. There remains the problem of explanation of how the excess pore pressure equivalent to the undrained strength could develop. The writer can suggest only that this would require complete structural collapse along one layer in the varved clay.

An effective stress stability analysis (Bishop, 1955) was made assuming the position of the zero water pressure line shown in Figure 8. Using $\phi' = 22$ degrees, and $c' = 0$, the minimum safety factor of 0.9 was obtained from a number of trial circles. Because of the consolidation of the clay, however, the assumption that $c' = 0$ is probably too stringent. On the other hand, the zero water pressure line probably conformed very nearly with the ground surface during the period of spring thaw. Since the effective stress analysis is influenced greatly by both the value of c' and the pore water pressure, this analysis cannot be considered a reliable confirmation of the method.

Conclusions

It has been the purpose of this paper to illustrate the behaviour of excavated slopes in normally consolidated varved clays. The experience at the Beattie Mine is by no means unique; dredging operations at Steep Rock Lake indicated similar behaviour (Legget, 1958). It seems usual for the varved clays on the Canadian Shield to have water contents above their liquid limits so that they are subject to earthflows.

The undrained analysis, although apparently successful for cases involving loading (Milligan *et al.*, 1962; Eden and Bozozuk, 1962) does not seem to be reliable in assessing the stability of some cuttings, particularly cuttings subjected to rapid changes in stress conditions. Experience at both Steep Rock and the Beattie Mine indicates that Terzaghi's rule concerning the critical height of a slope is a good indication of stability. Hence, it is suggested that deep cuts in these clays should be carried out by a system of benches and berms, with the height of the upper benches less than the critical height.

The effective stress stability analysis appears to be a more reliable indication of stability than the undrained or total stress analysis, but it is difficult to derive a realistic value of c'.

Acknowledgments

This study was conducted with the kind co-operation of Mr. W. R. Salter, President, Beattie-Duquesne Mines Limited. Mr. R. Gilhuly of the mining company at Duparquet assisted greatly in giving access to the mine records and in the search for information. Mr. F. E. Patton of Kitchener, Ontario, former Mine Engineer, provided a number of photographs taken from 1943 to 1946 and was helpful with his criticism and observations. The writer was assisted during 1961 by Professor K. Van Dalen of Carleton University, Ottawa, in both the field work and in the preparation of plans and profiles from the mining records. Mr. M. C. van Wijk of the Photogrammetric Research Section, Division of Applied Physics, National Research Council, made the plan from aerial photographs, which provided the basis for the stability analysis. Finally, the help in testing provided by his colleagues in Soil Mechanics Section DBR/NRC is gratefully acknowledged by the writer.

This paper is a contribution from the Division of Building Research, National Research Council, and is published with the approval of the Director who was first consulted about the failure when the Division started its work in 1947. The paper is one of a series being prepared within the Division to present constructive results derived from the careful study of engineering failures, when these can be undertaken with the agreement of the responsible authorities and it is seen that they provide information of value to the engineering profession.

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