Soil engineering at Steep Rock Iron Mines, Ontario, Canada
Legget, R. F.

Publisher's version / Version de l'éditeur:

Proceedings of the Institution of Civil Engineers, 11, pp. 169-188, 1959-07-01

NATIONAL RESEARCH COUNCIL
CANADA

DIVISION OF BUILDING RESEARCH

SOIL ENGINEERING
AT STEEP ROCK IRON MINES, ONTARIO, CANADA

BY

ROBERT F. LEGGET

REPRINTED FROM

PROCEEDINGS OF THE INSTITUTION OF CIVIL ENGINEERS
VOL. 11, OCTOBER 1958, P.169 - 188.

(DISCUSSION REPRINTED FROM VOL. 13, MAY 1959, P.93 - 117)

TECHNICAL PAPER NO. 74
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA

JULY 1959

C 4873

PRICE 75 CENTS

This publication is being distributed by the Division of Building Research of the National Research Council as a contribution towards better building in Canada. It should not be reproduced in whole or in part, without permission of the original publisher. The Division would be glad to be of assistance in obtaining such permission.

Publications of the Division of Building Research may be obtained by mailing the appropriate remittance, (a Bank, Express, or Post Office Money Order or a cheque made payable at par in Ottawa, to the Receiver General of Canada, credit National Research Council) to the National Research Council, Ottawa. Stamps are not acceptable.

A coupon system has been introduced to make payments for publications relatively simple. Coupons are available in denominations of 5, 25, and 50 cents, and may be obtained by making a remittance as indicated above. These coupons may be used for the purchase of all National Research Council publications including specifications of the Canadian Government Specifications Board.

(By permission of the Council of the Institution of Civil Engineers, London: Excerpt Proceedings, vol. 11, pp. 169–188, October 1958)

Paper No. 6304

SOIL ENGINEERING AT STEEP ROCK IRON MINES, ONTARIO, CANADA

by

Robert Ferguson Legget, M.Eng., M.I.C.E.
Director, Division of Building Research, National Research Council, Canada

For discussion at an Ordinary Meeting on Tuesday, 18 *November,* 1958 *at* 5.30 *p.m., and for subsequent written discussion*

SYNOPSIS

Steep Rock Lake, in north-western Ontario, Canada, had to be dammed and drained in order to gain access to large deposits of high-grade iron ore beneath its surface. Lake bottom deposits proved to be varved clays with natural water contents higher than their liquid limits, thus proving to be unstable when disturbed. Ultimately, almost 300,000,000 cu. yd of such material will have been removed from the lake bed in the development of the several major ore bodies. Dredging has been used for this major excavation operation, using suction and cutter-suction dredges. Stable slopes adjacent to the two open pits were successfully designed using the principles of soil mechanics.

General description

One of the original water routes to the Canadian West, in following the chain of rivers and lakes between the west end of Lake Superior and Lake of the Woods, included a stretch of the Seine River. Approximately 140 miles to the west of the modern cities of Port Arthur and Fort William, this river passed through an N-shaped lake, called Steep Rock because of the precipitous rocky cliffs which distinguished its northern shore. The location (Fig. 1) is at the heart of some of the most typical Canadian Shield country, glaciated pre-cambrian bedrock with some coverage of glacial soils in which grow spruce and birch, interspersed with a network of streams, rivers, and lakes.

2. The location is roughly 100 miles to the north of the iron mines of the Messabi and Vermilion Ranges in Minnesota. Interest in the possibility of iron ore on the Canadian side of the border is therefore long-standing. An Indian found some ore near Steep Rock in 1882. A note on the possibility of there being iron ore beneath the waters of the lake appeared on a geological map published in 1897. It was not, however, until 1926 that any real exploration was started and not until 1938 that any diamond drilling was done into the bed of the lake, working off the winter ice-cover. Geophysical studies were also made off the ice. Iron ore of unusually high quality was found in three major deposits. Today, the proved reserves are at least 300 million tons. Even the

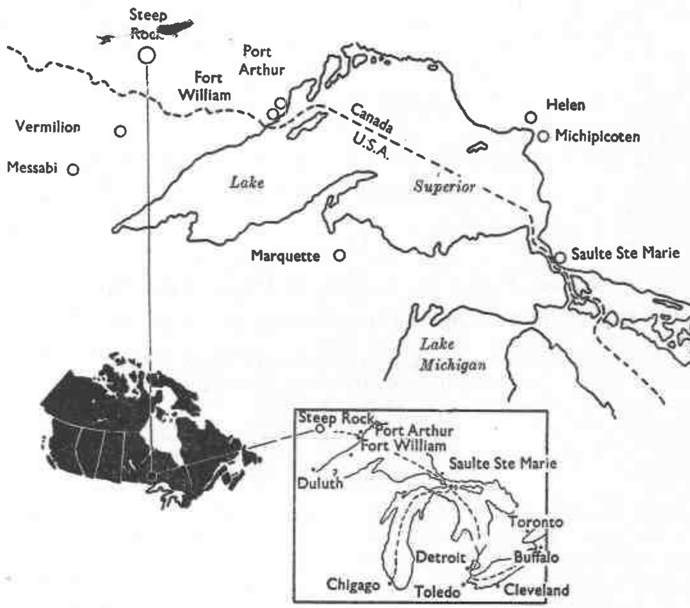

FIG. 1.—KEY MAP SHOWING LOCATION OF STEEP ROCK LAKE

early indications, however, warranted the sinking of a test shaft and drift in 1939. Water was encountered in the drift as the ore body was approached. As a result of this experience, and of extensive engineering studies, it was eventually decided that the lake should be drained to permit economical large-scale open-pit mining.[1]

3. The Seine River, with a drainage area of 1,800 sq. miles, empties into Steep Rock Lake. The drop of 100 ft from Marmion Lake was utilized in a power house generating 12,000 kVA, feeding into a power system to the west. Exhaustive studies disclosed no alternative to abandoning this station, in the interests of the river diversion. Fortunately it proved possible to arrange with the Hydro-Electric Power Commission of Ontario to supply enough power from their Nipigon system, to the east, over a new 110,000-volt transmission line, to replace that previously generated and for all mining operations. The equipment in the abandoned power house was tied in with the new line to serve as two synchronous condensers.[2] The structure itself served as the upper cofferdam. Two gravel-filled steel sheet-pile cofferdams closed two narrow gaps between the Middle and West Arms of the lake. The main part of the lake, and that under which the three ore deposits had been found, was thus isolated (Fig. 2, pp. 172, 173).

4. Careful study of the country to the north of Steep Rock Lake showed that it would be possible to divert the entire flow of the Seine River around the lake by lowering the level of Finlayson Lake and excavating through three

[1] The references are given on p. 188.

obstructions to provide a new water route. The spillway at the existing power house was therefore raised to take care of possible future flood conditions; two deep rock cuts were excavated; a small control dam was built on one of the lakes incorporated in the new route; Finlayson lake, about 15 miles long by 1 mile wide was lowered by means of a 1,350-ft tunnel; a wide and deep cut was excavated through a massive terminal moraine; and a new river channel cleared from the outlet of this cut to a junction with the existing river. This complex of civil engineering operations involved the excavation of 582,320 cu. yd of rock and 1,184,450 cu. yd of soil. The job was effectively completed between April and December 1943, despite the relative inaccessibility of most of the sites, the rough terrain, and the large volume of excavation.[3, 4, 5]

5. All the work so briefly summarized was carried out to a closely integrated construction schedule. The first civil engineering contract was not awarded until April 1943 but all the works were so far advanced, with all major excavation complete, that the pumping-down of Steep Rock Lake was started on 15 December of the same year. All the ancillary civil engineering work was complete by April 1944. Despite the soil problems with which this Paper s concerned, the first rock surface of ore body B was exposed by October 1944 and mining began immediately, ore being shipped via Superior, Wisconsin, until the first shipment could be made over the specially improved C.N.R. line to Port Arthur on 21 July, 1945. A new ore dock had here been constructed for discharging Steep Rock ore into large ore-carrying vessels for its transport to various steel plants on the Great Lakes.[6]

6. Once started, open-pit mining of the B ore body proceeded steadily until late in 1953 by which time 9,165,844 tons had been removed. The open pit having then reached an average depth of 375 ft below the rock surface (about 500 ft below the old lake water level), it was necessary to change over to conventional underground mining methods, since the ore body is about 150 ft wide and almost vertical. The extensive preparatory work for this change involved the excavation of a deep shaft and of an inclined conveyor drift 3,735 ft long. Meantime dredging and pumping were proceeding on the site of the A ore body and open-pit mining started here on 25 July, 1953. Dredging of the area between these two ore bodies, beneath which more ore has been discovered, is now proceeding; mining is expected to start here in the early spring of 1960. Production is now averaging about 2,500,000 tons/year; this may be increased to 5,500,000 tons/year within the next few years.

7. It may be seen from Fig. 2 that the C ore body is separated from the other ore locations by the full length of the East Arm of the lake, a distance of almost 2 miles. The bed level of this part of the lake was only about 90 ft below the original water level so that the initial pumping soon isolated the deep pool overlying the C ore body. Accordingly it proved convenient for the owners, Steep Rock Iron Mines Limited, to lease this third ore body for development quite independently of their own operations. A lease was therefore arranged with the Caland Ore Company Limited, a subsidiary of the Inland Steel Company of the United States, and this company is at present engaged in the final stages of their dredging work. Although all the experience of the Steep Rock Company has been made available to the Caland Ore Company, the two operations are quite separate, the Caland Ore Company having their own engineering staff and consultants. The paragraphs which follow relate only to the work of Steep Rock Iron Mines Ltd.

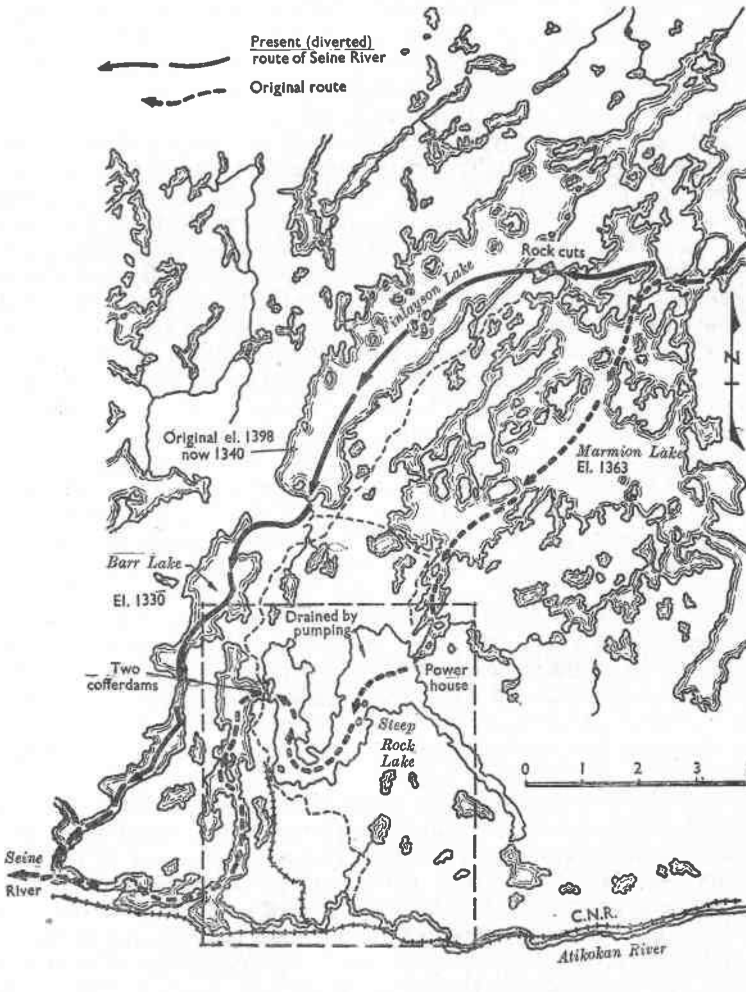

FIG. 2a.—GENERAL PLAN

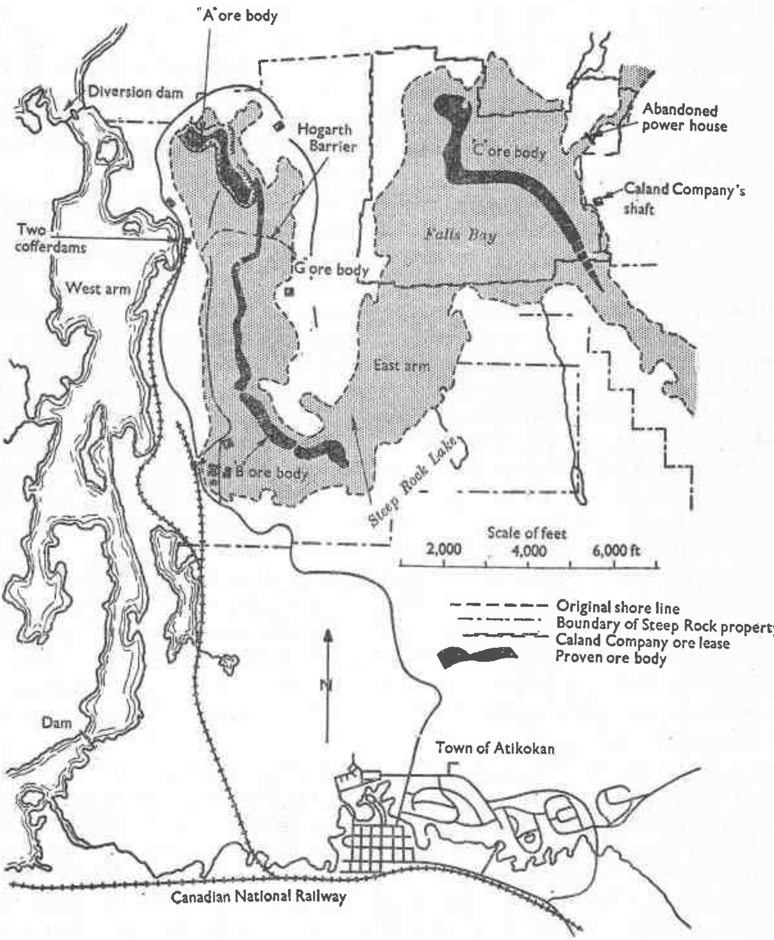

FIG. 2b.—PLAN OF STEEP ROCK LAKE SHOWING THE MAIN ENGINEERING WORKS MENTIONED IN THE PAPER

The soil problem

8. The Author's first sight of the soil problem at Steep Rock Lake was on 25 April, 1944. Pumping had been in progress since the previous December; the water level had been drawn down about 65 ft. The thick ice cover had been repeatedly broken as the water fell during the winter; the resulting huge jagged blocks of ice formed a weird picture, stretching up both arms of the lake as far as one could see. But they were melting, under the influence of the warm spring sun, and so there was evidence of surface-water flow all around. Soil was moving too, along all the banks, in small dribbles in some places, in the form of huge slides in others. As the lake bed was exposed, its slope near the old shore was seen to be very steep in places; it was here that the major slides occurred. One of these involved at least 350,000 cu. yd which slid into the still flooded lake bottom in the course of a very few minutes.

9. The mine authorities were justifiably worried since this was an unexpected turn of events. It was not difficult to show, however, that the slides were natural phenomena due to two main causes. The sudden drawdown in water level was disturbing the natural equilibrium of sediments long deposited. In all critical slopes this was leading to a readjustment of profiles. This could be attributed to excessive pore-water pressure and to the change in effective soil weight. At the time, however, it was more useful to describe this natural and inevitable process as "accelerated geology"—the normal physical–geological process of slope adjustment taking place in days instead of centuries, because of interference with natural water levels. A few of the slides were of a rather different character, however, being caused by internal erosion of the material at the toes of the slopes. Ground-water from the rocky drainage basin percolated beneath the lake deposits whenever pervious strata permitted; this process naturally followed the change in the water level.

10. There was almost nothing that could be done to stop these first early slides. At that time there was nothing on the surface of the shrinking lake itself except the barges carrying the pumps and they were located some distance from potential slide areas. The necessary precautions were taken to keep all equipment around the shores of the lake away from obviously unsafe areas. In consequence, remarkably little material loss was sustained (practically none after the first major slide).

11. It was possible to assure the mine authorities that these drawdown slides were a passing phase of the unwatering operation and that, as soon as inevitable natural slope adjustments had taken place, the situation could then be studied. At the same time, the suggestion was advanced that every possible step should be taken to "capture" concentrated surface flows coming down the rock gullies towards the old lake shore so that they would be prevented from flowing under the now-exposed lake bed material. The main intent of the suggestion was to eliminate, to the greatest extent possible, toe erosion due to seepage through pervious strata, now exposed in the lake bed deposits above water level. An incidental advantage would be to limit the danger of surface erosion of the newly exposed bed materials.

12. Consistent with the many other items of preliminary work then demanding attention, the mine authorities followed this suggestion, even to the extent of diverting one of the larger streams, by means of a small concrete dam, over a

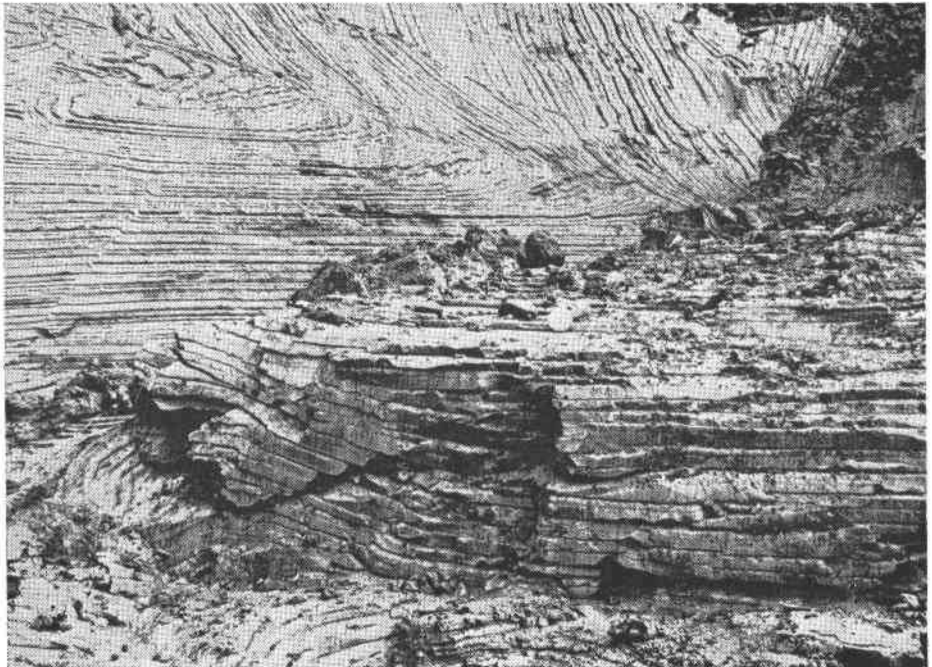

FIG. 4.—TYPICAL EXPOSURE OF VARVES IN EXCAVATION DEEP IN THE OLD LAKE BED, SHOWING DISTORTIONS AS FREQUENTLY ENCOUNTERED

FIG. 5.—EXCAVATED SILT FLOWING TOWARDS LAKE AFTER BEING DUMPED FROM DRAGLINE BUCKET

FIG. 6.—GENERAL VIEW OF OPEN-PIT OPERATION AT B ORE BODY IN 1950 LOOKING TO THE S.W. FROM THE EASTERN BAR

By courtesy of the Photographic Survey Corporation Limited, Toronto, Canada

FIG. 7.—AERIAL VIEW OF THE B OPEN-PIT OPERATION IN 1950, LOOKING N.W.; WEST ARM IN LEFT BACKGROUND, POOL STILL OVER A ORE BODY IN TOP RIGHT; SCALE INDICATED BY $2\frac{1}{2}$-CU.-YD SHOVEL AT WORK IN PIT

By courtesy of the Photographic Survey Corporation Limited, Toronto, Canada

Fig. 8.—Aerial view of A ore body with open pit in operation, looking south; dredging is proceeding in the middle arm in the left background behind the Hogarth Barrier; west arm (right background) is in use as a disposal area. The centre feature is a large belt conveyor and gallery. Scale is indicated by 2½-cu.-yd shovels at work in the pit

height of land into the West Arm of the lake. Before this diversion could be effected, however, dramatic evidence of the need for such simple water-control measures was provided by the fact that in the course of 6 weeks, the spring flow of this very small stream eroded a gully, 36 ft deep and more than 60 ft wide, in the level surface of the exposed lake bed immediately adjacent to the original shore line.

13. When the ice disappeared, it revealed generally a wet and sloppy surface of jet-black, gelatinous-looking mud—so common a feature of northern Canadian lake beds. Beneath this was found a uniform but very wet grey clay-like soil which preliminary borings had shown to extend to depths of 250 ft and to overlie a thin but compact layer of glacial till immediately above the rock surface. This soil profile varied in only a few locations, these being on the south shore of the lake where some sand beds were found, usually exhibiting marked cross bedding. Walking on the freshly exposed surface was impossible without sinking at least up to ankle height, except at points where it was obvious that erosion had removed the loose surface deposits.

14. The first practical problem to be faced was how to gain access to the exposed lake bottom so that work could start. So urgent was this problem that there was no time available for any detailed study. A rough idea of the bearing capacity of the soft upper deposits was gained from personal experience in "over-mud travel" with the aid of wide boards and even on occasion using snow shoes. It was argued that the strength of the lower deposits could not be less than that of the near-surface material. Accordingly, simple calculations were made to determine the requisite height of fill for spreading the wheel-loads of the loaded trucks that were to be used. This was found to be 4 ft. A fine deposit of naturally well-graded sand and gravel, containing even some binder material, was found near to the desired location for the start of the access road into the lake area. The placing of the necessary embankment therefore started in April 1944 and the road was ready for use right down to the proposed open-pit area by the time that the first excavation operations were ready to begin. Even though the road was soon carrying a steady succession of Euclid trucks weighing 30 tons each (and later 45 tons) when filled with ore, the road performed with complete satisfaction. It was well maintained with a power grader. Together with other similar roads built later, it served continuously until 1949 when the original road had to be dredged out to permit mining operations to continue under it.

15. All the early test drilling, generally carried out by working off the winter ice, had been carried out in the search for ore, and for the delineation of the extent of the ore bodies once they were discovered. The overburden which had to be penetrated was then regarded merely as a nuisance since it had to be cased and so impeded progress in reaching the rock surface and commencing diamond drilling. No special attention was therefore paid, at the time, to the character of the overburden, but its depth was recorded and its general clay-like character was noted. This information was sufficient to show the mine authorities that the volume of soil they would have to move before the rock surface could be reached and cleared was very great, to be measured in millions of cubic yards. It was accordingly decided, even before pumping had started, that the only satisfactory method of dealing with such vast quantities of soil would be by dredging, and subsequent pumping. This proved to be a wise decision. Almost all the excavation of soil from the lake bed adjacent to the B ore body, apart

only from some trimming, had been carried out by suction dredges, aided by cutting and by sluicing with high-pressure water jets; similarly that adjacent to the A ore body has been removed by cutter-suction dredges.

Soil studies

16. In view of the incomplete information on the soils to be encountered given by the preliminary test drilling, it was clear that one of the first operations to be conducted as soon as the area around the B ore body was even reasonably accessible should be a more detailed investigation. Test boring down to rock surface was therefore started with light drilling-rigs just as soon as the equipment could be dragged over the mud to the sites of proposed test holes, well in advance of road building and other construction operations. Twenty-seven test holes were put down to depths of about 200 ft below the original water level of the lake (water depth being about 125 ft). Undisturbed soil samples were taken at approximately 5-ft intervals. Many hundreds of tests were performed on these samples. Standard mechanical analyses were conducted to determine grain-size distribution. Fig. 3 presents graphical records of tests on typical samples from which it can be seen that the material could be described on the basis of grain size as silt rather than clay. In view of the relatively recent geological origin of the soil particles, this result was not too surprising despite the clay-like appearance and consistency of the soil.

17. When natural moisture contents and the standard Atterberg limits were determined for typical samples, however, results were obtained which (at the time) were quite unusual. Fig. 9 shows these results for a typical borehole. It will be noted that in the case of every sample, the natural moisture content is

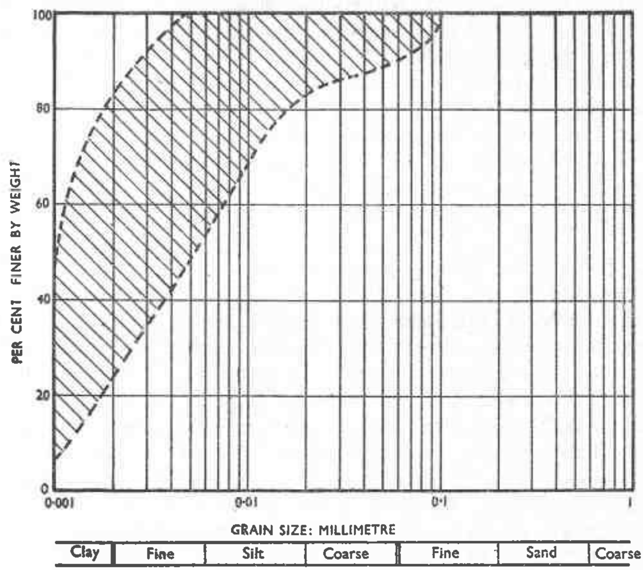

Fig. 3.—Envelope of graphical records of grain-size determinations for varved clays

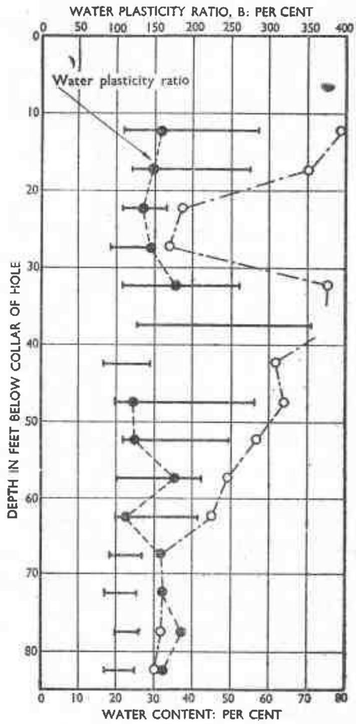

FIG. 9.—LOG OF TYPICAL BOREHOLE AT B ORE BODY

higher than the liquid limit, and usually appreciably so. Although naturally at first suspect, this feature was carefully checked and confirmed for the first group of samples tested; it was later found to be true for every Steep Rock sample which the Author has tested. These results were in sharp contrast with the firm and solid appearance of the soil samples, when examined in their undisturbed state as obtained from the sampling tubes. The excess of water was revealed, however, as soon as a sample was remoulded between the fingers. The original structure disappeared and the solid lump of damp soil quickly became a wet and sticky slurry.

18. The scientific implication of this soil property was as interesting as its practical significance was important. Further and more detailed study of the samples revealed the layered structure called "varving", which is characteristic of fine-grained sediments of glacial origin. It was clear that the soil had been deposited in the lake in some rhythmic pattern, the deposition being of such a nature that the soil particles were arranged in an unusual way, best described as having a "honeycomb" structure. This internal soil structure would explain the high natural water-contents of all samples, and also the fact that, when once this structure was disturbed, the original character of the soil was permanently

destroyed. The soil structure was intimately associated with the presence of varves, a feature of great interest to geologists. Varves are alternating light and dark layers of soil, usually very thin but occasionally 1 in. or more in thickness. They are thought by many to represent summer and winter deposits, a succession of varves thus being a small part of the geological time-table. Fig. 4 is a typical exposure, including also some of the contortions of the normally horizontal varves which raise interesting scientific speculation. As excavation proceeded, the varving was found to persist (as had been expected) throughout the whole of the silt deposit, the resulting exposure being probably one of the most extensive ever seen. The Author was privileged to introduce Dr Ernst Antevs to the Steep Rock varves in 1946 and the results of his studies have been published.[7] The Author and his colleagues have also published results of their studies.[8, 9]

19. While the unwatering programme steadily proceeded all attention had to be concentrated on the practical problem of handling safely the soil in the lake bed. Accordingly, the soil samples obtained from the boreholes mentioned in § 16 were subjected not only to the tests mentioned in § 17 but also to simple strength tests. The finer soil particles could with accuracy be described, in part, as fresh rock flour. The combination of this type of soil with the unusually high natural moisture contents confirmed earlier field observations as to the instability of the soil when disturbed. At the same time, and for the same reason, it could be predicted that when the soil was disturbed, as by dredging, there would be no difficulty in transporting it by means of water.

20. Mainly because time was so limited, the first strength studies were carried out as unconfined compression tests, using cylindrical samples about $1\frac{1}{2}$ in. in diameter and 3 in. long. Reasonably consistent results were obtained for cylinders carefully cut from "undisturbed" core or block samples. Attempts were made to determine the corresponding strength of the soil after remoulding but it was never possible, in this early work, to make up a complete cylinder of soil from the "slurry" which resulted from remoulding. Later tests gave results of from 4 to 8 for the sensitivity. Much more extensive testing of soil samples was done subsequently, some of it reported upon by W. J. Eden,[9] but as the results were not used in relation to the first excavation work, they need not be recounted here. It should be noted, however, that all the early soil testing, the results of which were so urgently required for practical purposes, was carried out upon samples selected almost at random from the material available, and with no special attention given to the varves. In more detailed work, carried out later, it was found that there were significant differences between almost all the properties of the material in the light and dark layers in the varves.[9] Since all the varves except those immediately overlying the thin layer of glacial till, i.e. close to rock level, were very thin—ranging from about $\frac{1}{2}$ in. to "paper thickness"—it was clear that these internal variations in soil properties could not have affected significantly the strength of the soil in place, despite their scientific importance, although the varving was carefully considered in relation to slope stability calculations.

General excavation procedure

21. When plans for the necessary excavation work in the lake bed, preliminary to the open-pit mining operation, were being worked out, little thought was given to the actual properties of the soil to be moved beyond the fact that it was "grey mud", as shown by the records of the overburden penetrated in the preliminary diamond drilling. Two dredges were acquired together with the neces-

sary discharge pipes and pontoon supports. When the initial slides took place (see §§ 8 to 10) and as the wet and "sloppy" surface of the lake bottom was gradually uncovered, concern developed that the main problem was going to be that of holding any soil at all in place: there were visions of having to pump out the entire rock basin of the lake before mining could start. Even these fears, however, did not affect the decision to engage in an extensive dredging programme. The first dredge was put into operation early in 1944, immediately over the B ore body. The second dredge was built and put into operation in the early spring of 1945. The first dredge discharged into the East Bay; the second dredge discharged into the Middle Arm where the slurry ran by gravity for approximately 1 mile northward where it was picked up by large water pumps, which had been used originally to pump out the lake, and discharged into the West Arm of Steep Rock Lake. The dredges were 15-in. suction dredges powered by 750-h.p. motors mounted on wooden hulls, 28 ft wide by 60 ft long. The dredges were moved by power winches mounted on the fore deck. Each dredge pump was equipped to operate in any one of seven stages, depending upon the amount of head required. The dredges were capable of lifting the slurry approximately 180 ft. When those limits were reached, it was necessary to provide booster pumps to continue to the final stage of the operation.

22. Soil exploration and soil testing were therefore carried out concurrently with the start of the dredging programme. This added a sense of urgency to the work which is unusual in soil studies. The closest liaison was maintained between those responsible for the various operations, with the result that the dredging and excavation programme was continually under review during the first year of operation, being adjusted whenever field experience or laboratory test results showed this to be necessary or desirable. The major change in thinking came when the results of the undisturbed-soil sampling showed that beneath the sloppy surface material was soil which, at least when undisturbed, was reasonably stable. As soon as excavation beneath the loose surface material was possible, various procedures were tried. It was soon found that, prior to disturbance, the silt was so "stiff" that it would stand temporarily with vertical faces up to 10 or 12 ft high. Correspondingly, its initial stiffness was such that it required considerable force to break into the solid mass of silt. The use of high-pressure water jets was an obvious possibility; early trials showed this to be a satisfactory method of excavation.

23. With the exception of a relatively small fraction involved in the final "trimming", all of the soil initially removed from the vicinity of the B ore body was pumped by the two dredges, after the breaking-loose of most of it by means of water from monitors or water jets. These followed generally the practice adopted in placer mining and so were not so unfamiliar a feature of a major mining operation as might at first sight appear. Water pressure from 70 to 100 lb/sq. in. was used with brass nozzles, swivel mounted, having $2\frac{1}{2}$-in. circular orifices. Supply lines were 24-in. spirally-welded pipe, supplied by two of the original water pumps (in series) used to pump out the lake. Distribution lines to the monitors varied from 10 to 16 in. dia. The operators achieved real skill in operating the monitors which were used on a 24-hour basis, 7 days a week, throughout the entire year. Winter operation naturally presented its special problems but only rarely was monitoring stopped because of low temperatures, the jets being operated at temperatures as low as $-40°$F. Operation of the dredges presented even less difficulty in the winter, the intake operating beneath

the ice cover (which naturally facilitated access to the hulls). When necessary, ice broken on the surface was removed by dragline. Temperature of the discharge would usually be slightly above freezing, owing to the water density gradient beneath the ice, and so no major trouble with frozen discharge lines was ever experienced. The high solid-content of the discharge (up to 20%) also assisted in winter operation.

24. Once the first working face for the jets had been established, bulk excavation was carried out by cutting away at the bases of vertical faces of the stiff grey silt. The soil would first break off, usually in large blocks, often by the collapse of the full face. In keeping with the fundamentally unstable character of the silt, once it had been disturbed from its natural position, it would quickly lose its initial stiffness and, under the action of the jets, it would quickly become fluid. Diluted by the discharge from the monitors, the soil soon had the consistency of cream and so would flow readily towards the dredge pool whence its removal by pumping was an easy matter. The only fatality directly attributable to the soil work at the mine occurred when a frozen face of silt broke suddenly, a large lump of frozen material crushing one of the operators fatally.

25. Reference to the instability of the silt relates to the fact that its natural water content is always higher than the liquid limit. Once, therefore, the natural structure of the soil is destroyed, the excess of contained water tends to liquefy the soil, thus destroying immediately its in-situ stiffness and strength. Clearly revealed by laboratory tests and easily demonstrable in small hand specimens, this unusual soil property was vividly demonstrated by one of the very first excavation jobs to be done. A small cut had to be excavated near the shore in order to give a uniform grade to the access road (§ 14). This was done by means of a small drag-line. Digging was tough but once the bucket discharged its contents of sticky, stiff "clay" (as the men called it), the material turned to a liquid as soon as it hit the ground, and proceeded to "flow" away quite literally as may be seen in Fig. 5, facing p. 174, the length of the mud stream there seen being over half a mile.

26. Once the men engaged upon the excavation operations had got used to this unusual soil property, they quickly gained a healthy respect for the soil's inherent instability. They followed loyally the special precautionary instructions given (as they knew) on the basis of laboratory tests on small-scale samples. It was, however, singularly difficult and usually impossible to persuade new pit superintendents and foremen, coming to Steep Rock from other mines, that this was no ordinary soil that they were dealing with. Their distrust of the "academic" advice they were given was removed, in almost every case, only after instructions had been neglected and the man concerned had actually witnessed a small slide. No further argument was then needed. Most fortunately, these "demonstration slides" were all small and did no significant damage. This detail of "human engineering" is mentioned since it was at once so understandable and yet so frustrating. Similar neglect of this unusual property of Canadian glacial silts had led to serious troubles in other northern areas. How to gain general recognition of this unusual soil is a special Canadian soil problem.

Excavation at the B ore body

27. Although the planning of the detailed sequence of dredging operations proved to be one of the most interesting phases of Steep Rock work, it was peculiarly a local problem with little general application. After the dredge

at the B ore body had worked its way into the lake bottom, there was some mass movement of the loose surface material towards it. This soon stopped; monitoring was started and the dredge then operated from specially excavated pools in which it could float, and to which the material moved by the sluicing flowed naturally. A year later, in 1945, the first dredge was joined by the second dredge which had been assembled in the area adjacent to the main pumping station and floated a mile southward to the B ore body. Both dredges, later aided by booster pumps, continued to move the monitored silt into the Middle Arm (to the west) and East Arm (to the east). Test boring had revealed the fortunate existence of two subsurface "bars" to the east and west of the B ore body, ridges of bedrock covered by glacial till. It was possible to utilize these two bars in the design of the slopes which separated the open-pit area from the Middle and East Arms. The initial work of the dredges was substantially finished by 1949, although the open pit had been in operation from late in 1944. It was decided some time later to excavate more of the soil near the open pit as a precautionary measure before starting underground mining operations. For this purpose a small 18-in. cutter-suction dredge was purchased and worked at this "cleaning-up" job from July 1953 to November 1956. The three dredges moved in all about 21 million cu. yd of soil. The open pit was mined until 5 December 1953; since then ore has been mined underground. The pit had still to be maintained in an open condition for the safety of the underground workings; no difficulty has been experienced in achieving this.

EXCAVATION AT THE A AND G ORE BODIES

28. Test drilling had shown that in order to uncover the area of the A ore body and the newly discovered G ore body, a much larger excavation programme would be necessary, involving about 110 million cu. yd of soil. In order to expand the mining operations as quickly as possible, it was decided to divide this dredging programme into two projects, one for the A ore body involving about 55 million cu. yd and the second project to follow over the G ore body, involving some 53 million cu. yd of soil. The early experience gained at the B ore body was naturally invaluable in planning for this further operation and pointed to the practicability of carrying out the work by contract, despite the unusual character of the soil. After much study, a contract was negotiated with Construction Aggregates Limited of Chicago who purchased a large, all-electric cutter-suction dredge for the job. The dredge had a hull measuring 133 ft by 40 ft and 10 ft deep; it had a 36-in. suction pipe, cutter equipped, a 30-in. discharge pipe, and was operated entirely electrically, the main motor being rated at 6,000 h.p., driving the main pump through a Kingsbury thrust bearing. Assembly of the dredge started in May 1950; it was at work by November and engaged upon the major excavation by the beginning of 1951. Based on the earlier experience, excavation was carried out by the dredge cutting vertical faces in the silt to depths of up to 35 ft. when supported by the water in the pool, swinging the hull on fixed spuds through about 120°, and pumping the disturbed silt as a thin slurry. In this way the one machine was able to move up to 55,000 cu. yd in a 24-hour shift, pumping it (with the aid of booster pumps) against heads which varied finally up to 400 ft. The silt was initially discharged near the cofferdams through a 400-ft tunnel into West Bay and later through a 1,900-ft tunnel into the north end of West Bay. In order to obtain sufficient make-up water for the large dredge, and to allow for the discharge of the water being pumped into

East Bay by the two smaller suction dredges, a tunnel 4,800 ft long was driven from East Bay to Middle Bay in May 1949. Additional make-up water was obtained from the West Arm.

29. Owing to the fact that progress of the dredging at the A ore body was not fast enough for planned mining operations, a second dredge was obtained, comparable in size with the first. It started to work in October 1952; the two machines finished their work in December 1954, having then cleaned out the area between the Hogarth Barrier (Fig. 2b) (see § 35) and the north end of this part of the lake, open-pit mining of the high points of the A ore body having started in January 1953. Winter operation caused some difficulties, mainly because of the scope of the operation. The surface ice could not be maintained as a solid sheet; it was finally necessary to clear out much of the broken ice adjacent to the dredges. Almost 75,000 cu. yd of ice had to be removed each winter. The cost of removing the 55,736,000 cu. yd finally handled under the first part of this contract was $5,683,860 for operation and $14,132,225 for capital equipment, an operating cost of about 10 cents/cu. yd and a total cost of only 36 cents/cu. yd, writing off the entire capital cost against this one job.[10]

30. Further exploration had revealed the existence of another ore body (G) between the A and B ore bodies, along the Middle Arm of the lake, beneath the area into which much of the silt from the B excavation had been discharged. The two dredges were therefore retained, and are now at work on this further excavation, pumping again directly into West Bay with the aid of booster pumps. As was to be expected, the initial dredging here is a very much tougher proposition than any of the previous work. The disturbed silt, having once lost its artificial "honeycomb" structure, has settled into a relatively compact mass and is mixed with waste rock from large dumps, requiring hard cutting for its removal. It is estimated that about 53 million cu. yd will have to be moved before the G ore body will be available for open-pit mining. Still more ore has been discovered beneath the waters of the West Arm (the H ore body) but whether this will be mined in the foreseeable future is still problematical.

31. The two dredges had to be moved to the new location to start excavation over the G ore body. After careful study of all possible alternatives, it was decided to move them overland so as not to interfere with mining operations. With only some strengthening of the hulls, both dredges, weighing about 900 tons each, were hauled out of their final pool areas in February and March 1955, and over hard frozen roads a distance of about 2 miles, involving a rise in elevation of more than 200 ft. Each hull was mounted on three sets of large crawlers, giving a three-point suspension; hauling was by means of five heavy tractors and four 34-ton ore-haulage trucks. It was a spectacular but highly successful operation, resulting in a saving over all alternatives of at least $500,000.

Slope stability

32. When the unusual character of the Steep Rock silt had been determined and methods developed for its efficient excavation, the next major soil problem was the determination of the slopes to which it could safely be trimmed. Initially, as already noted, it was thought that almost all the silt at the B ore body would have to be removed. Early strength tests upon silt samples, and the observed behaviour of the material when cut to vertical faces by the monitor jets, showed that this was too pessimistic a judgement. At the same time, and since the entire open-pit operation would be dependent upon the satisfactory per-

formance of soil slopes adjacent to it should all the silt not be removed, the decision to leave as much of the silt in place as possible was one of the most critical in the whole Steep Rock operation. The decision was made, however, on the basis of engineering judgement aided by the results of soil mechanics studies; it has proved to be sound. The experience gained in implementing this decision at the B ore body was of great assistance with a much more critical slope design for the A ore body. In neither operation have any failures occurred, despite the fact that the total height of the excavated silt around the pits was 120 ft.

33. At the B ore body, as can be seen from Fig. 7, the open pit is flanked on the north by a steep rock face, from which much waste rock had to be removed. To the east and west are the two bars already noted (§ 27). Only to the south, therefore, had soil slopes to be depended upon for the safety of the open pit. Here, however, there was a rise of 200 ft from the lowest rock level at the lip of the open pit to the old shore line, which was about 1,000 ft away, resulting in a great crescent-shaped area subtending about 120°, 4,000 ft wide at the open pit and about 5,000 ft in extent at the old shore line. Depths to rock over this area ranged up to 150 ft, the soil being almost all the unstable silt; the stability of this entire area had to be assured. (Fig. 6 gives a general idea of this area.)

34. It was clear, from strictly practical considerations, that the entire area could not be finished off to one uniform slope; benching would have to be used, not only to provide level working areas for the monitor operators but also as a safety control for any small slides that might occur. Early trials showed that it was possible for the operators to trim a reasonably smooth slope merely with the water jets from their monitors. The steepest natural slopes, found in the unwatered bed of the lake, were about 1 in 3 and so this slope was adopted as that to which the excavated slopes were trimmed. The bulk of the excavation had been completed before it became necessary to make final decisions regarding the finished slopes to be used so that it was not until the summer of 1948 that this was done. Hugh B. Sutherland was then at the mine, engaged on research studies; he carried out a series of unconfined compression tests using a simple testing device (made in the mine machine shop) and obtained fairly consistent values of about 4 lb/sq. in. for the shear strength of undisturbed silt samples. Using these results, he determined that the safe vertical depth in the silt would be 22 ft. By considering the possibility of a circular slide taking place, assuming uniformity in the silt 1 in 3 slopes, rises of 20 ft, followed by 50-ft berms, and using the $\phi = 0$ analysis, a limiting rise of 54 ft was established. An excavation plan was therefore developed with vertical rises of 20 ft on a 1 in 3 slope between berms of steadily increasing width from the first two of 50 ft.[11] To these dimensions the entire slope was finished off successfully. The berms were graded slightly towards their inner edge, so that there would be no possibility of surface drainage running over the edge on to the slope. Drainage was collected by grading the shallow surface-drainage ditches cut at the back of each berm towards the most appropriate outlet at each level. Once finally trimmed, the slopes remained quite stable. One or two small flow slides occurred but these were not related to the slopes as such but to some disturbance of the silt at a point which proved to be critical (traceable in all cases to carelessness).

35. The A ore body is located in the roughly circular northern end portion of the Middle Arm of the lake. To isolate it required blocking off the remainder of the Arm by some suitable structure spanning across from one rock face to the other. Test borings showed that the silt extended to depths of up to 350 ft

below original water level at the most suitable location for the necessary dam, called the Hogarth Barrier. Based on a careful study of the test boring results, a comparison of them with known properties of the silt at the B site, the application of the design criteria used for the slopes at the B ore body, and a further personal investigation, K. L. McRorie (at that time Chief Engineer of Steep Rock Iron Mines Ltd) prepared a design for the slope of the Hogarth Barrier, even before pumping had revealed any part of the soil to be so used. When completed, the Barrier would have a total height, on its north face, i.e. on the side of the A ore body, of 160 ft. A slope of 1 in 3 was again adopted, with 20-ft rises between berms. Berms of a uniform width of 100 ft. were decided upon. The design was checked by W. J. Eden using test results obtained in research work upon tube samples of the silt from the Barrier. Tri-axial compression tests gave fairly consistent values for the undrained shear strength of about 5 lb/sq. in. and indicated an apparent angle of shearing resistance of about 5°. The berms were formed as the water level slowly fell and the shape of the natural dam was gradually carved out, by careful work with high-pressure water jets from the same monitors as had been used for the earlier work. The Barrier was successfully completed to the design noted. The rate of lowering the water level in the pool was strictly controlled, being lowered in 20-ft stages. This was naturally a vital factor in the design, permitting such drainage as did take place to develop gradually.

36. Careful control of surface drainage on all slopes was recognized as of vital importance from the outset; special precautions were taken to ensure that it was also always kept under control. It required only the smallest trickle off one of the berms to start gully erosion in the freshly exposed silt of the slopes. Fortunately, no trouble with excessive surface run-off was experienced in either location. It was the Author's hope, originally, that protection of the slopes could have been speeded by the planting of grass. Some experiments were conducted, using grass mixtures recommended by agricultural experts. In view of the areas involved, the seeding was a rather crude operation; possibly for this reason, little initial success was achieved. Even in the areas in which the black lake-bottom deposit had not been disturbed, poor results with seeding were obtained. (It was later found that the organic content of this black muck was only 10% by weight.) Eventually, over the course of 2 or 3 years, nature did what artificial seeding had not done; vegetation of varied kind gradually appeared all over the slopes. Once started, natural growth spread steadily until today the old lake bed is completely covered by vegetation. The great value of natural vegetation in slope protection has again been confirmed.

37. No accurate record has been kept of the number of "slides" at Steep Rock since the original drainage operation, but the Author has seen at least fifty slides, large and small. Not one of these was of the classical cycloidal form; all were surficial or flow slides. Having watched some small slides start and finish, and having examined many more soon after they occurred, the Author is certain they cannot be analysed only in terms of excessive pore pressure. Because the silt had a natural water content greater than the liquid limit, excessive pore pressure resulted from the failure, rather than caused the failure. These conditions in the disturbed silt caused it to flow, which removed the support from the adjacent stable silt which in turn collapsed, liquefied and started to flow, the movement progressing rapidly until stopped by some change in the soil or by the profile of the affected slope. No attempt was made to measure pore

pressures in the silt. The varving was enough in itself to render any such measurements meaningless. The sudden variations in soil type, quite apart from the varving, which were found throughout the entire lake area, would have the effect of making any measurements of very local significance and therefore of academic interest only. Installation of any measuring devices might have disturbed the soil from its natural state (possibly with disastrous results if the location had been a critical one).

Some special problems

38. Electro-osmosis was tried experimentally on some small samples of silt in the very early stages of the development, at the suggestion of the late E. P. Muntz. Some positive results were obtained but of such a limited nature as to render any application of the system, even in a restricted location, of questionable value. The extent of the silt which had to be stabilized made all further thought of applying electro-osmosis quite useless.

39. Boulders were frequently encountered in the excavation work, not in the silt itself, but along all old lake shore lines and as soon as the bottom of the silt, and so the top of the glacial till, was reached. This surface was very irregular At the B ore body, boulders created no special problems since they were easily moved by the water jets and accumulated in selected locations where they would cause no trouble. In the major dredging operation at the A ore body, however, they caused a lot of trouble since the suction dredges were not equipped with rock-catchers. The two dredges had to be stopped a total of 13,560 separate times, in order to clear rocks from cutter, suction line, or impeller. This resulted in the loss of 1,910 hours of pumping time, equivalent to almost 4 million cu. yd. This is the second occasion when the Author has encountered such rock trouble in a major dredging operation;[12] this note is therefore included here as a warning to those who may refer to this record in connexion with any comparable excavation work.

40. When it was planned to discharge silt into the West Arm of the lake, it was assumed that the silt would settle out easily, probably in lumps since it had been transported only a few thousand feet after being excavated from its original state. No trouble was experienced at first with the discharge from the small dredge but when the large cutter-suction dredge at the A ore body started its discharge, trouble soon developed owing to the fact that a small quantity of the very finest particles did not settle out as anticipated but travelled down the lake and so out into the Seine River. Discharge started in the winter of 1950. When the ice disappeared in the spring of 1951 distinct discoloration of the Seine River could be traced as far as Rainy Lake, a distance of about 80 miles. The Lake is an international water; fishing is still important on the river and in the Lake. A major problem was thus created. Every conceivable means of getting the fine particles to settle was studied but none were of any avail since those that were effective (such as using a deflocculent) were not only too costly on the scale that had to be contemplated, but they caused more polution to the river water than the fine inert silt particles which they were being used to cure. Finally, the decision had to be made to divert the Seine River again and close off the West Arm by means of an earth dam, thus converting it into a natural stilling basin. This possibility had been contemplated (although not for this purpose) when the original diversion work was carried out so that the new works were speedily designed and constructed, being completed in time to divert the spring flood of

1952 into the new channel of the Seine. Discoloration of the River was thus stopped, but at a cost of approximately $1,250,000.

41. Large settlements were to be expected when the varved clays were subjected to appreciable surface loading, since they were normally consolidated and possess a high initial void ratio, sometimes exceeding 2. Two examples may be mentioned. An area was set aside for necessary job workshops near to the B ore body. Because of local topography and the necessity for being as close as possible to the ore body, the workshops themselves were located over the varved clay contained in a former shallow bay of the lake. The clay varied greatly in depth, up to as much as 60 ft. The site was preloaded in 1945 with an 8-ft depth of rockfill; the workshops were constructed in 1950. Initial settlements were not significant, owing to the preloading. In 1953, however, owing either to the stripping operations lower down in the old lake bed, or to a conveyor raise driven under the area (in the development of the underground mining arrangements), the local ground-water level was suddenly depressed, causing further consolidation of the clay. From January 1953 to June 1954, new settlements up to as much as 18 in. were recorded. Fortunately, all the buildings had been constructed on raft foundations, resting on the rockfill still in place, so that no building suffered any serious damage in this period owing to the differential settlement, although the crane rails in the main machine shop had to be relevelled when settlement had almost ceased.

42. Construction of a railway embankment as a part of the spur line to the loading station for the A ore body became necessary in 1954. It was to cross the Narrows between the Middle and West Arms of the lake. The embankment had to be 85 ft high and 40 ft wide at its shoulders, and so would be 250 ft wide at its base. Since it crossed the Narrows close to the cofferdams retaining the waters of the West Arm from flowing into the Middle Arm, it was essential that no soil movement should take place either during or after the construction of the fill. Beneath the only possible location for the embankment was from 20 to 30 ft of typical varved clay. To obviate the possibility of a shear failure, counterweight fills about 50 ft wide and 40 ft high were placed on each side of the edges of the site of the main embankment. In one critical area, the clay was excavated by dragline and replaced with a rock key. The main fill was then built up in uniform stages, using waste rock hauled from the pit area. The dimensions of the counterweights were determined on the basis of circular arc stability analyses. The design adopted, again the work of K. L. McRorie, was successful in preventing any shear failure of the underlying soil. The main rockfill settled more than 3 ft owing to consolidation of the clay. It will be appreciated that, because of the varved structure of the soil, it is impossible to predict settlements with any degree of accuracy on the basis of laboratory consolidation tests upon small soil samples. In the first of the examples noted, some consolidation tests were carried out and the best attempt possible at the prediction of settlement was made. Some degree of success was achieved but the rate of consolidation in the field was more rapid than could have been determined from any of the laboratory tests; it is believed that this was primarily due to the varved character of the soil.

Conclusion

43. Fig. 6 epitomises soil engineering at Steep Rock Lake perhaps as well as any verbal description. The Author took this photograph on 8 July, 1950 when the open pit was in full operation, its bottom grade being then 500 ft below the

level of the Lake. The view was taken from the eastern bar, looking towards the old south shore of the lake. The benching of the silt may be clearly seen and, to the extreme left, one of the small "demonstration" slides which proved to be helpful in educating new pit superintendents. All the soil to be seen, with some vegetation starting to grow on the upper slopes, is the unstable silt previously described; all of it, if disturbed, would flow like soup. Even more impressive was the sight of the completed Hogarth Barrier, especially when viewed from the bottom of the A pit. Fig. 8 (facing p. 175) is a general view of the Hogarth Barrier as seen from the air. Mining operations proceeded in this pit, to a depth of 550 ft beneath the old lake level, protected with the full confidence of all concerned by this 160-ft-high natural dam, entirely made up of a singularly unreliable soil.

44. The fact that what originally looked like a quite hopeless situation, when the silt was first revealed in all its apparent instability, could be turned into so satisfactory a project was to some extent the result of a combination of engineering judgement and the application of the principles of soil mechanics. Far more, however, was it due to the quite remarkable way in which everyone concerned with this mining venture accepted the fact that the ordinary treatment in mining operations of soil as "mud" had to be forgotten, and the Steep Rock soil treated with the very greatest of respect, day and night, winter and summer, until stability of all slopes was assured. It is a pleasure to pay this unqualified tribute to the many men of Steep Rock who worked together in "licking" their soil problem so successfully that their iron-ore mining operation is now one of the most notable in North America.

ACKNOWLEDGEMENTS

45. The Author is indebted to Steep Rock Iron Mines Limited for permission to present the Paper.

46. Joseph Errington, the founder and first President of the Company, inspired the pioneer diversion programme. He was succeeded, in turn, by General D. M. Hogarth and M. S. Fotheringham. Among the many who have been associated with the soil engineering involved in the development of the Mine since 1944, are K. L. McRorie, M. W. Bartley, W. E. Bennett, S. G. Hancock. Since the start of the mine, Watkin Samuel has been the Consulting Engineer and Hugh M. Roberts the Consulting Geologist. To have worked with all of these men was a rare pleasure. Special mention must be made of Mr Fotheringham and Mr Samuel who were directly responsible for all decisions regarding soil engineering at Steep Rock, and of Mr McRorie for the design work which he did, as already noted.

47. The Author served as soils consultant to the mine, in close association with Mr Samuel, from 1944 until 1 August, 1947, when he was called to Ottawa to assume his present post, the tenure of which precluded further private consulting work. By that time the main decisions regarding the soil problems had been made, and it was known that the proposed open-pit operation could proceed safely. Through regular visits, the Author has maintained close touch with the further development of the mine. The mine authorities recognized the opportunities which the remarkable exposure of varved silts presented for research and kindly permitted the new Division of Building Research of Canada's National Research Council to use the mine as a soils laboratory for the special study of the silts which it contained in such volume. For two

summers, members of the D.B.R. staff (H. B. Sutherland, A.M.I.C.E., and W. J. Eden) spent several months at the mine in field research. Since that time regular visits have been paid by D.B.R. staff and the Author, and laboratory research has been carried out not only at Ottawa (by W. J. Eden) but in other soil mechanics laboratories with which D.B.R. maintains liaison.

References

1. W. Samuel, "Steep Rock Iron Mines, discovery and development". J. Engng Inst. Can., vol. 28 (1945), p. 4.
2. A. H. Frampton, "Power supply in the Steep Rock mining area". J. Engng Inst. Can., vol. 28 (1945), p. 150.
3. A. W. F. McQueen and C. N. Simpson, "Diversion of Seine River at Steep Rock". J. Engng Inst. Can., vol. 28 (1945), p. 10.
4. C. H. Hopper, "Diamond drills and well drills on the Raft Lake Canals at Steep Rock". J. Engng Inst. Can., vol. 28 (1945), p. 18.
5. N. S. Bateman, "Moving a river and draining a lake for open-pit mining of iron ore". Engng News Rec., vol. 133 (1944), p. 764.
6. J. M. Fleming, "Iron ore loading dock at Port Arthur". J. Engng Inst. Can., vol. 28 (1945), p. 26.
7. Ernst Antevs, "Glacial clays in Steep Rock Lake, Ontario, Canada". Bull. Geol. Soc. Amer., vol. 62 (1951), p. 1223.
8. R. F. Legget and M. W. Bartley, "An engineering study of glacial deposits at Steep Rock Lake, Ontario, Canada". Econ. Geol., vol. 48 (1953), p. 513.
9. W. J. Eden, "A laboratory study of varved clay from Steep Rock Lake, Ontario". Amer. J. Sci., vol. 253, 1955, p. 659.
10. W. E. Bennett, "Dredging operations over Hogarth ore body". Trans. Canad. Inst. Min. Metall., vol. 59 (1956), p. 78.
11. K. Terzaghi and R. B. Peck, "Soil mechanics in engineering practice". J. Wiley and Sons Inc. (Chapman and Hall Ltd), 1948, p. 366.
12. R. F. Legget, "Development of a pulpwood shipping harbour, Forestville, Quebec". J. Engng Inst. Can, vol. 36 (1953), p. 1287.

The Paper, which was received on 3 February, 1958, is accompanied by six photographs and four sheets of drawings, from which the half-tone page plates and the Figures in the text have been prepared.

Written discussion on this Paper should be forwarded to reach the Institution before 15 December, 1958, and will be published in or after May 1959. Contributions should not exceed 1,200 words.—Sec.

Paper No. 6304

Soil engineering at Steep Rock Iron Mines, Ontario, Canada †

by

Robert Ferguson Legget, M.Sc., M.I.C.E.

Discussion

Professor A. W. Skempton (Professor of Civil Engineering, Imperial College, London) said the excavation described was probably the deepest ever made in soft clay and he would like to see a typical cross-section, including the position of rock.

49. During the pumping out of the lake a number of large slips had occurred. It must have been extremely difficult to investigate them at all thoroughly, but, owing to their magnitude, even a rough analysis would be interesting.

50. The clays in the lake must have been deposited at least 6,000 years ago, so that they would be fully consolidated under their own weight. In those conditions it seemed inevitable that their strength would show a decided increase with depth, but he had the impression that that increase had not been observed. If that was the case, then there was something of a paradox, and Professor Skempton hoped that the Author would give some further information on the question.

51. The lake clays were extraordinarily interesting, and from a Paper written by the Author's colleague Mr W. J. Eden, at Ottawa, Professor Skempton had tried to collect some data on the light and dark layers which were such a characteristic feature of the deposit. These were given in Table 1. Would the Author in his reply make any necessary corrections, for a representative set of data would be very interesting. There was, however, one point which was extremely puzzling. The third line from the bottom of Table 1 related to what was called the activity, which represented, to some extent, the mineralogy of the material. In the light layer this figure was only 0·25, which was extraordinarily low, and even in the dark layer it was only 0·6. Yet in Mr Eden's Paper it was said that in the dark layers there existed montmorillonite, a mineral which imparted a high activity to the clay.

52. However accurate the figures in the Table 1 might or might not be, they at least

TABLE 1

	Light layers	Dark layers
Period of deposition	Summer	Winter
Water content	30	90
Liquid Limit	28	80
Plastic Index	8	50
Clay fraction ($<2\mu$)	30%	85%
Activity (P.I./clay fr.)	0·25	0·6
Shear strength	450 lb/sq. ft	850 lb/sq. ft
Sensitivity	about 10	10

† Proc. Instn civ. Engrs, vol. 11, p. 169 (Oct. 1958).

showed definitely that there was a great difference between the light and the dark layers, and that must impart a very considerable anisotropy in the clay. What effect had that had on the stability, and had it been allowed for in the calculations? Varved clays were fairly widespread, certainly in the northern parts of Europe and America, so that anything which could be learnt about them was likely to be of fairly general interest.

53. It would also be noted that there was a highly significant difference in the grain size of these layers. The clay fraction given in Table 1 was 30% for the light layers and 85% for the dark. In other words, the dark layers were very much finer-grained than the light layers. This seemed to correspond with the classical idea of varved clays, namely that the dark layers were deposited in the winter, when the lake was frozen over, and that the light layers corresponded to the unfrozen periods when material was being brought in by streams, when, in general, the grains were of larger size. The Author seemed slightly sceptical about the nature of these clays, and in particular whether or not they were truly varved in the foregoing sense of the word. He knew that others shared that scepticism, not only about Steep Rock Lake but about varved clays in general. If the theory just mentioned was correct, and on the whole it had been widely accepted for at least half a century, each pair of light and dark layers must represent a year. This idea had been investigated very thoroughly in Scandinavia. In Fig. 10 the line marked IV represented the position of the last notable moraine of the

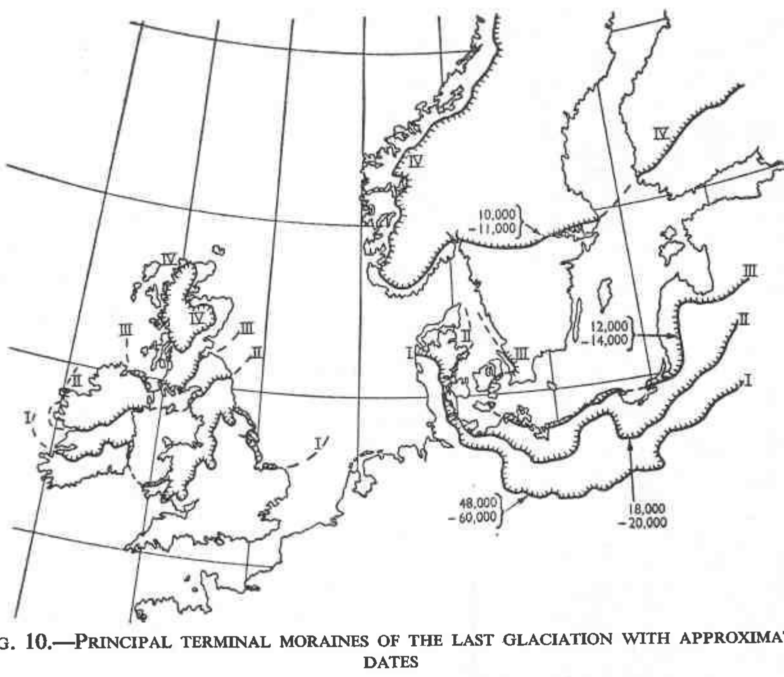

FIG. 10.—PRINCIPAL TERMINAL MORAINES OF THE LAST GLACIATION WITH APPROXIMATE DATES

last glaciation, from Oslo to Stockholm and up into Finland, and incidentally in the Highlands of Scotland as well. De Geer, who had first worked scientifically on these varved clays, had attempted to date some of the late glacial phenomena by counting the layers, and by this laborious method of counting the number of varves in the lakes left to the north of the moraine during the retreat of the ice sheet he had published a figure, long ago, of approximately 10,000 years for the date when that retreat had started.

There had been some uncertainties in his estimate because of gaps in the data, but in 1939 a closely similar figure had been obtained in Finland, where the data were more complete. Within the past few years the radio-carbon method of dating had been brought to bear on this problem, and the date of 10,000 years had been confirmed very closely indeed by what was a completely independent, and absolute, method of dating. Professor Skempton felt that this could not be a coincidence and that, certainly so far as Scandinavia was concerned, the classical explanation was correct. It was tempting to imagine that it must apply in general in Canada as well. Was the Author still sceptical or did he feel that Canadian clays differed in some essential respects from those in Scandinavia?

Dr L. F. Cooling (Head of Soil Mechanics Division, Building Research Station, D.S.I.R.) said that during one of the Author's visits to Garston he had arranged to send a good undisturbed 9-in. cube of the varved clay from Steep Rock. That had been examined in the laboratory, mainly in order to find out the differences between the materials comprising the light and the dark bands in the varves. Detailed work of this kind, carried out by Mr Legget and Mr Eden, had already been published, but Dr Cooling felt that it might be of interest to give a brief summary of the results obtained in his laboratory, particularly where they concerned points which had not been covered by the earlier investigations.

55. When the sample had first been opened from its paraffin wax packing it had not been easy to see the varves. Fig. 11 represented an attempt to measure the moisture-

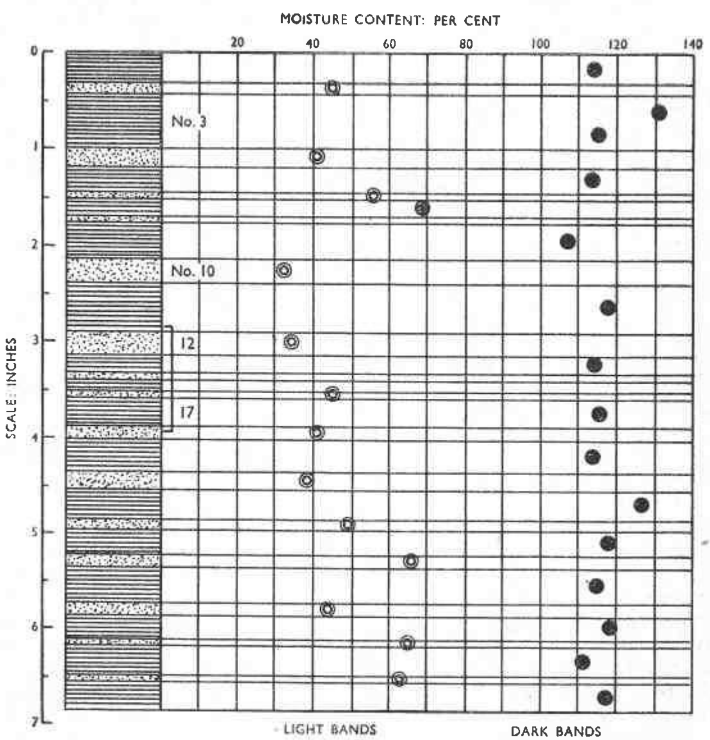

FIG. 11.—VARIATION IN MOISTURE CONTENT IN VARVED CLAY FROM STEEP ROCK LAKE

content distribution down 6–7 in. of the sample, and it showed the very pronounced difference between the dark bands and the light bands. In the dark bands the moisture content had been between 112% and 127% of the dry weight, while in the light bands the moisture content had been mainly between 30% and 50%. With the very thin bands it had been difficult to separate the material and values of up to 60% had been obtained. After drying for a short period it had been possible to distinguish the individual bands clearly and to obtain samples from each.

56. Mechanical analysis tests had been carried out on about a dozen samples carefully taken from individual bands, and, while the grain-size-distribution curves lay within the envelope indicated by Fig. 3, there had in fact been a distinct difference in the curves for the dark and light bands, as shown in Fig. 12. The dispersant used had

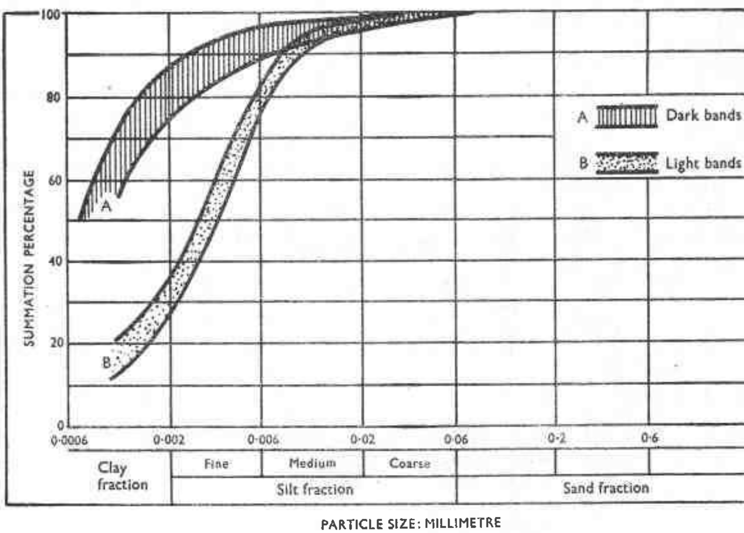

FIG. 12.—GRAIN-SIZE-DISTRIBUTION CURVES FOR VARVED CLAY FROM STEEP ROCK LAKE

been N/100 sodium oxalate, which had been found to be more effective than sodium silicate. In the light bands about 70% weight was in the medium fine silt range (0·02–0·002 mm), with only 30% clay size (i.e., less than 0·002 mm); in the dark bands there had been more than 70% in the clay range.

57. An attempt had been made to see whether or not the difference between the varves could be related to the mineralogy, and for that purpose differential thermal analysis and chemical tests had been carried out at the Building Research Station, and X-ray diffraction tests had been made by Mr Walker, then of the Macaulay Institute at Aberdeen. From the X-ray analysis it had been concluded that both the light and the dark bands contained the same rock-forming materials, quartz, feldspar, hornblendes, and tourmaline. With regard to the clay minerals, it had been thought that both bands contained some kaolinite but that, while the light band contained a clay mineral of the chlorite type to the extent of about 20%, the dark band contained about the same quantity of montmorillonite. The thermal-analysis results indicated the same sort of thing, namely that the dark band contained a much larger quantity of absorbed water, but apart from this there had not been a great deal of difference. The chemical analysis (see Table 2) indicated that the light band contained more silica and sodium and less iron, aluminium, and magnesium. It had been concluded from these tests that the main difference between the two bands was that the light band contained a clay mineral

TABLE 2

Description	Dark band No. 9	Light band No. 10	Dark band No. 19	Light band No. 20
	Per cent by weight, calculated on to the theoretical H_2O and CO_2 free material (ignited)			
SiO_2 . . .	58·32	66·20	59·05	65·10
Fe_2O_3 (Total) (iron) . .	7·35	5·66	5·80	5·10
Al_2O_3 . .	17·42	12·73	18·85	16·27
TiO_2 . . .	0·91	0·53	0·79	0·60
CaO . . .	4·60	4·97	3·36	3·29
MgO . .	4·88	3·28	5·08	3·18
Mn_2O_3 . .	0·13	0·07	0·09	0·07
Na_2O . .	2·55	3·49	2·94	3·45
K_2O . . .	3·12	2·67	3·04	2·59
SO_3 . . .	0·68	0·48	1·04	0·34
	99·96	100·08	100·04	99·99
Loss on ignition of original sample	44·85	24·50	50·00	10·60

with little interlayer water, which was fairly inactive, whereas the dark band contained a clay mineral which had a much greater quantity of interlayer water.

58. The results of plasticity tests fitted in with this conclusion and also raised a further point which seemed to be related to mineralogy. The technique used at the Building Research Station and elsewhere in the United Kingdom for the determination of the liquid limit of soils was to carry out the test directly on fresh and not air-dried material, whereas air drying was the technique adopted in the A.S.T.M. standard. This slight difference in technique made a pronounced difference to the results for the dark bands only, as would be seen from the following typical figures:—

	Original	Air dried	Oven dried at 105°C
Dark band . .	120–125%	85–90%	55–74%
Light band . .	39%	37%	35%

Using values for the fresh material, the activity of the dark-band clay was 1·2–1·3, and for the light-band clay about 0·4–0·5.

59. The plastic limits for both dark and light bands ranged from 26% to 31% in the fresh state and were not much affected by oven drying. He did not think that the effect of oven drying on the liquid limit of the dark band was due to the small quantity of organic matter it contained, but rather to the effect of drying on the lattice of the hydrated clay mineral. Lambe and Martin[13] reported similar effects on soils containing nontronite and other clay minerals. In view of this effect, it was not surprising that the Author had found that his values of liquid limit were appreciably less than the natural moisture content.

60. Consolidation tests had been carried out on carefully prepared samples from individual varves, and typical results were shown in Fig. 13. It would be seen that for the dark band the initial void ratio was as high as 3·5, and the shape of the P/E curve was characteristic of a sensitive meta-stable type of clay structure. The effect of remoulding on the sample was also clearly shown. There seemed to be no doubt that

---

[13] References 13 *et seq.* are given on p. 117.

this dark band was highly flocculated when laid down and on remoulding would tend to go into a closer packing and release free water. On the other hand, the light bands had a void ratio of about 0·9; their structure was not very compressible and the material was probably not flocculated to any extent on deposition. However, being primarily a silt deposit the increase in pore pressure introduced by water derived from remoulding adjacent dark bands would tend to make it lose stability very rapidly.

61. In § 20 the Author contended that "these internal variations in soil properties could not have affected significantly the strength of the soil in place." Dr Cooling was not quite sure what that phrase meant, and perhaps the Author would explain it in more detail. Dr Cooling agreed that the structure of the clay was something which

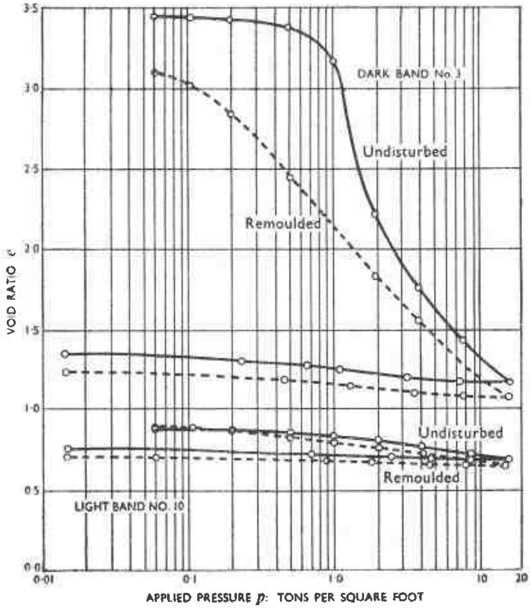

FIG. 13.—PRESSURE/VOID-RATIO CURVES, STEEP ROCK LAKE

had to be accepted and that there was no obvious practical means of improving the strength of the deposit; but he felt that the behaviour of the clay as evidenced in the practical job was very much concerned with the structure of the varved clay. The intimate juxtaposition of two types of band, one of which had a great deal of water in it and tended to structural breakdown on deformation, and the other a silty band which lost much strength when its water content increased, constituted a type of soil structure which would behave in an unstable fashion when disturbed. That would go a long way to explain the rapid deterioration into a mud run after slipping.

Mr G. A. Kellaway (Principal Geologist, Geological Survey of Great Britain) said that excavations such as those at Steep Rock Lake could be a very important source of basic geological information. The laminated silt and clay had been described as varved. Many varved deposits showed some degree of graded bedding in addition to seasonal banding but it would appear that these deposits were not graded. However, glacial and post-glacial lake sediments would be expected to show considerable variation in grain size and bedding owing to the complex conditions which occurred in nature. In illustration he exhibited some slides of aerial photographs taken at about 10,000 ft, showing the mouth of the Slave River at its junction with the Great Slave Lake. Unlike some lakes the waters of the Great Slave Lake were normally clear, and the dense grey turbidity current can be seen entering the lake in summer. The turbid stream divided around islands in its course leaving clear water on the lee-side, and threw out divergent jets, plumes, and clouds of silt, while the main current plunged to the depths of the lake. The process was very similar to that seen in the Lake of Geneva, where some of the geological implications were described by Sir Henry de la Beche[14] in 1853.

63. Kuenen,[15] in 1951 had explained some of the features of Scandinavian varve clays as being due to the presence of turbidity currents. The Author had referred to the Paper by Antevs,[7] where these and other factors were discussed at length, but parts of that Paper were difficult to follow and Mr Kellaway felt the need for more facts. In particular he would be glad to know some more about the slumped or folded beds (Fig. 4). He inferred that the Author attributed these to drawdown taking place during periods of natural lowering of the water-level of the lake. Could any further information be given about the distribution of these beds, of their contacts with the undisturbed strata, and of the effect of their presence on the validity of the varve chronology?

64. It would also be interesting to know the angle of the steepest slope found on the top surface of the lake sediments before the latter were disturbed. Perhaps the original contours of the lake bed were available and could be given.

Mr A. L. Little (Associate, Messrs Binnie, Deacon & Gourley, Consulting Engineers, London) observed that one of the most impressive features of the Paper, describing very considerable difficulties which had been successfully overcome, was the almost astronomical size of the quantities involved. It was stated in the synopsis that 300,000,000 cu. yd was the total of the overburden which would have to be removed. He regarded it as particularly significant that hydraulic methods had been chosen for excavation and transport. By conventional dry methods—scrapers, dumpers, face shovels, and so on —maximum rates of excavation were continually increasing and rates of the order of 40,000 cu. yd/day were being reached. In fact, on two large dams on the Missouri River, Garrison dam and Oahe dam, peak rates of 1,000,000 cu. yd/week had been achieved, but had not been sustained for any length of time.

66. Mr Little was concerned with the design of a rather high earth dam which would contain about 70,000,000 cu. yd of material and would involve 57,000,000 cu. yd of excavation. One of the difficulties was that placing the material in the dam was likely to require rates which, by dry-fill methods, were unprecedented, and in consequence much consideration had been given to hydraulic methods. The Author's description was of great value to him. Could the Author give some more information and perhaps opinions based on his experiences?

67. At Steep Rock the material had a very high natural water content, which, according to the Paper, was higher than its liquid limit, although Dr Cooling had thrown some doubt on that; but at least by comparison with the liquid limit the water content had been very high. At the same time, because of its structure, the soil, when it was disturbed, became a liquid and flowed readily. Those characteristics must have been of considerable help with hydraulic methods of excavation, whereas it was easy to imagine the difficulties which they would have caused with dry methods of excavation and transport. Would the Author advocate using hydraulic methods with other types of material, and, in particular, with dry silty or sandy materials?

68. It would appear from the Paper that the work had been divided into two parts, one part being done by direct labour and the other part let to contract. It would be interesting to have more details of the contract. The last line of § 29 seemed to suggest that the contractor had been reimbursed for the capital cost of his dredges, but Mr Little was not clear whether that was so or not. It was also mentioned that the work had been divided up between two 15-in. and one 18-in. dredges and two 26-in. dredges used by the contractor, Construction Aggregates Limited. Detailed figures were not given for those operations, but crude calculations based on the data given suggested that the

two large dredges, which shifted 55,000,000 cu. yd, had been considerably more efficient in this work than the three smaller ones, which had shifted 21,000,000 cu. yd in roughly the same time of 4 years. The Author had referred to difficulties with boulders and fairly large figures were given for down-time because of those difficulties, but had there been any other trouble as well? An objection to the use of very large dredges seemed to be that if they broke down, production ceased entirely, whereas with several small units there was more flexibility. On the other hand, it might now be considered that a large dredge was so reliable that there was no fear of breakdowns, and the time for which it was necessary to stop to make replacements could be foreseen and included in the works programme. He would like the Author's views on that.

Mr W. H. Ward (Deputy Head, Soil Mechanics Division, Building Research Station, D.S.I.R.) said that the Author had very kindly given him the opportunity in 1950 to visit Steep Rock and examine the deposits.

70. The Paper gave the impression that the only sediments in the lake basin were varved silts. He knew that the Author was aware that this was not the case, but, in order to avoid any misunderstanding, he wished to comment on some of the salient features of the influx of sediments into glacier lakes and to describe a typical section through the lake bed deposits.

71. Glacial lakes were usually fed by water and sediments of fairly local origin, which entered from a number of different directions. The run-off, coming mainly from melting snow, lasted for only a short time each year, but it was intense, and the peak intensity varied considerably from year to year. The peak flow occurred soon after the whole snow profile reached the melting point, and might last only a week or two. It was during this short time, when the ground surface started to thaw and the whole scene was alive and roaring with water and slush, that most of the sediments were brought into the lakes.

72. One would therefore expect to find in glacial lake beds plenty of coarse sediments of various origins forming deltas near their points of entry, as well as sediments of mixed origins in the more central parts of the lake. Evidence might also be expected to be found of considerable changes in lake levels and deposits specially associated with the advances and retreats of the local glaciers.

73. Fig. 14 was a cross-section of the Steep Rock Lake bed deposits, which Mr Ward had recorded with the help of Mr F. L. Peckover in 1950. It showed some details of the southern shore of the lake on a north-south section towards the eastern end of the "B" ore body, but well to the west of the eastern bar. A view of the section was given in Fig. 6, where the southern shore was on the left-hand side of the photograph. (It should be noted that a section through another part of the lake bed would give a different record; some deposits would be missing and others had taken their place, while some would be common.) Dealing with the succession of sediments and commencing at the highest level, at the top there was an outwash delta or beach deposit of bedded sands, sandy gravels, alternating grey clay and red silty sand beds, and bedded fine gravels with grey clay lumps. The clay lumps were interesting, because they were often contorted pieces of a laminated sediment and represented redeposition of an earlier lake sediment. The bedding in this series was parallel to the sloping beach and the series was about 70 ft thick.

74. The next series had been, at the time that he had been there, obscured to some extent by man-made outwash, but it consisted of laminated red sand and grey clay. These alternating layers of material of different origin suggested that their entry into the lake might have occurred at slightly different times in the same summer season. The beds varied in thickness from a fraction of an inch to many inches, and they lay roughly horizontal. Their total thickness was about 40 ft. At more than one level the beds had slipped and the layers had become highly contorted.

75. All trace of red material was absent in the next series of beds, and the grey clay and silt laminated material was reached about which Dr Cooling, Professor Skempton, and the Author had spoken. This series, to Mr Ward's mind, compared with the rest

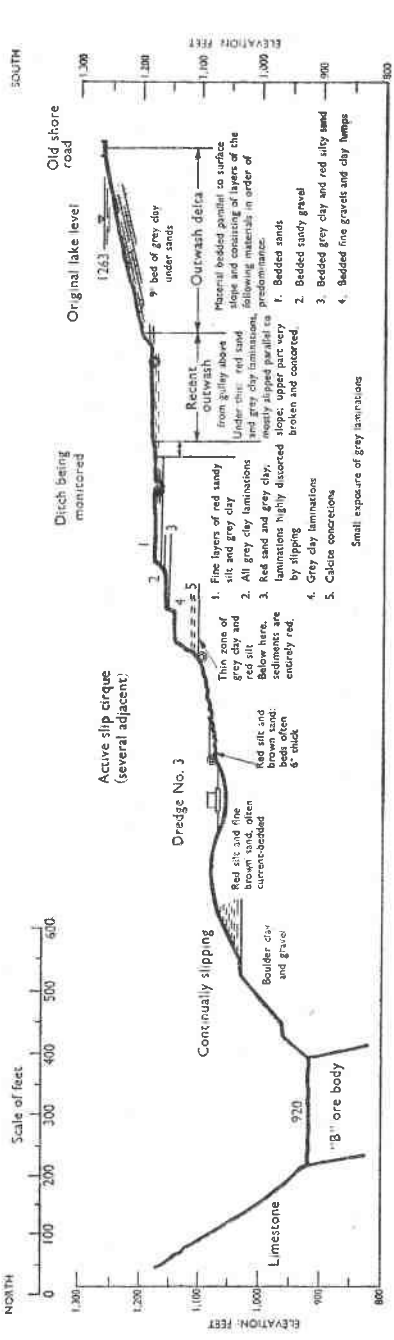

FIG. 14.—APPROXIMATE NORTH-SOUTH SECTION OF SEDIMENTS ON LINE OF No. 3 DREDGE AT STEEP ROCK LAKE ("B" ORE BODY). OCTOBER 1950

of the material in the lake, probably represented a time when the lake had been relatively quiescent from a glacial point of view and the glaciers had retreated a long way from the lake. Those beds were about 50 ft thick and towards the base there were several layers of calcite concretions, which could have been derived from the local limestone that forms the cliff on the northern shore of the lake.

76. The lowest sediments, above the boulder clay and the ore body, were about 70 ft thick and were all red or reddish in colour. They consisted of red silt and reddish-brown sand in roughly horizontal beds. The beds were often 6 in. thick and the sands were frequently current-bedded.

Mr H. B. Sutherland (Reader in Soil Mechanics, University of Glasgow) said that, as was mentioned in the Paper, he had spent some months at Steep Rock in the summer of 1948, while attached to the staff of the National Research Council of Canada. During his stay, the question of the slopes to which the excavation through the varved clay were to be trimmed had been under discussion. The rapid mining of the iron ore had naturally been the main purpose in the minds of those supervising the work and unnecessary excavation of clay would have delayed the mining and increased the costs. A 5% increase in excavation represented about £100,000 in operating costs alone. As was stated by the Author in § 26 there had been on occasion a tendency to win ore at the expense of stability of the excavations above. If that attitude had been allowed to continue, slope failure might have occurred which would have disrupted the operations of the mine for a considerable time.

78. To counter that attitude, the Author had described how small "demonstration slides" had been used. In addition, a series of lectures on the stability of slopes had been given during the summer of 1948 to the supervisory staff of engineers and foremen. Mr Sutherland felt that those meetings and discussions had helped in establishing a co-operative attitude to proposals regarding the slope stability problem.

79. When considering the stability of the slopes, two possible types of failure had been envisaged: first, failure by flow slide, and secondly, failure by slipping over a curved surface, normally considered as circular. A number of flow slides had occurred in the period immediately after the draining of the lake and had been caused by the sudden drawdown of the water level. Flow slides would have developed at a later period if excess pore pressure had developed in coarser layers in and below the varved clays. Terzaghi and Peck[16] described how flow slide failures had occurred in varved clays in the Hudson Valley at intervals of 20 years or so owing to build-up of pore pressures after periods of excessive rainfall and which had caused high adjacent water-tables. Mr Sutherland's impression of the flow slides at Steep Rock had been that the critical period for them would be confined to the period shortly after drawdown and during the bulk excavation. If the slopes survived this period, further flow slides would be unlikely if precautions had been taken to minimize the future build-up of pore pressure. To achieve this, it had been recommended that there should be close control of surface drainage towards the pit around the perimeter of the original lake. Provided the pore pressure was controlled, there would be an increase in slope stability with time arising from the increased effective overburden pressure and shear strength.

80. There has been no information available on which to base a flow slide analysis and there had been no possibility of obtaining information on potential pore pressures which would have allowed a comprehensive analysis to be made. The installation of pore-pressure gauges had been discussed, but they had not been considered to be a practical proposition.

81. Terzaghi and Peck[16] had considered the question of flow slides and shown that if the pore pressure could build up to a level to eliminate the friction in an underlying water-bearing layer, then the critical height of the slope located above the layer to ensure no flow slide was reduced to about the height to which a vertical face could stand unsupported. If it had been assumed that this extreme condition could occur at Steep Rock, it would have meant that no iron ore would have been mined, since the excavations could not have been carried out. A compromise had been made to give some

safeguard against flow failure, in that the vertical rise between berms had been limited to the height at which a vertical face could stand unsupported. This limiting height, of about 20 ft, fitted in with the requirements from the circular arc analysis and also with the operational procedures at the site.

82. When considering the slope design, a value had to be obtained for the shear strength of the clay. No equipment had been available for shear-strength testing, and a combined trimming and compression-test machine had been constructed in the mine workshops. A number of unconfined compression tests had been made on block samples taken from representative sections of the excavations and an average value of shear strength obtained. A check on this value was given by carrying out controlled full-scale failure tests for shear strength on the site. Opportunities for such tests rarely occur in practice, but the conditions for them had been ideal at Steep Rock since the clay had to be removed in any case.

83. Monitors had been used to trim vertical faces in the clay, and the heights at which failures of those vertical cuts occurred had been measured. Knowing the height to which a vertical face could theoretically stand unsupported, and the unit weight of the clay, its shear strength could then be calculated. The average value of shear strength so obtained agreed closely with the average value obtained from the unconfined compression tests.

84. This average shear strength had been used, in conjunction with Taylor's curves,[17] to obtain limiting heights to which given slopes should be taken. A general pattern for excavating slopes and berms had therefore been established. In making recommendations along those lines, it had been pointed out that they were essentially a guide and must be applied with regard to the observations and experience of the engineers at the mine. It had not been intended to be a rigid specification but to be used with good judgement. Had any modifications been made to the slope-trimming recommendations during the course of the work at B ore body and subsequent excavations?

85. In § 37 the Author commented on the nature of flow slides and stated that they could not be analysed only in terms of pore pressure. In his explanation of the mechanism of progressive failure, perhaps he would explain how failure developed in the first instance if excessive pore pressure was not the cause.

Brigadier J. B. Brown (Deputy Director, Fortifications and Works, War Office) described how in 1945 in Rangoon he had cleared some teak docks of silt, which had accumulated during the war, by using a number of trailer fire pumps.

Mr F. L. Cassel (Director, LeGrand Adsco Ltd) described an investigation in North Wales where a pumped-storage reservoir site in which extensive varved clay, of more normal characteristics than the Canadian clay, had been found unsuitable because the sudden drawdown once a day might have led to the occurrence of slips.

The following contributions were received in writing.

Mr W. K. Mak (Messrs Jenkins & Potter, Consulting Engineers) observed that on the basis of grain-size distribution, the material in question had been classified as silt rather than clay, and that the material could be accurately described as fine rock flour. It was interesting to find that the grain-size-distribution curve of a Boston clay passed right through the middle of the shaded envelope of the grain-size-distribution chart as shown in Fig. 15.

89. If the upper limiting curve, the bordering curve to the right of the shaded area in Fig. 3, was taken out and plotted on to the U.S. Bureau of Soil triangular classification chart the resulting point fell on the "clay" area, as shown in Fig. 16. The data of Fig. 9 had been plotted as numbered circles on to the plasticity chart of the Unified soil Classifications together with some other fine-grain materials as shown in Fig. 17. The present material appeared to coincide very well with that of the glacial lake deposits

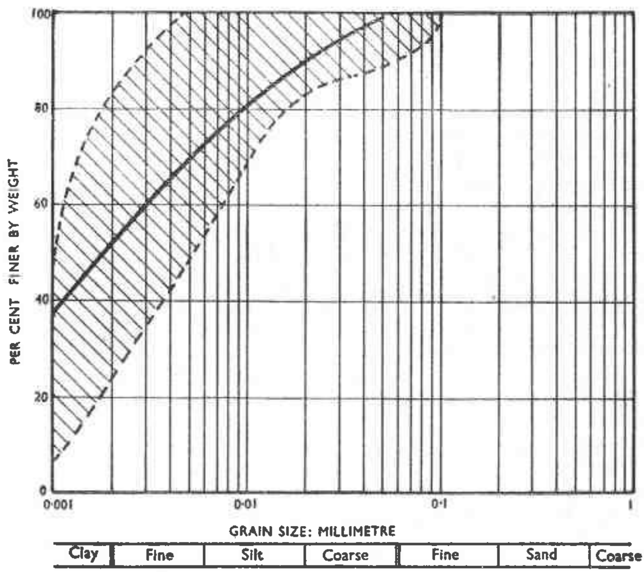

FIG. 15.—GRAIN-SIZE-DISTRIBUTION CURVE OF A BOSTON CLAY SUPERIMPOSED ON FIG. 3

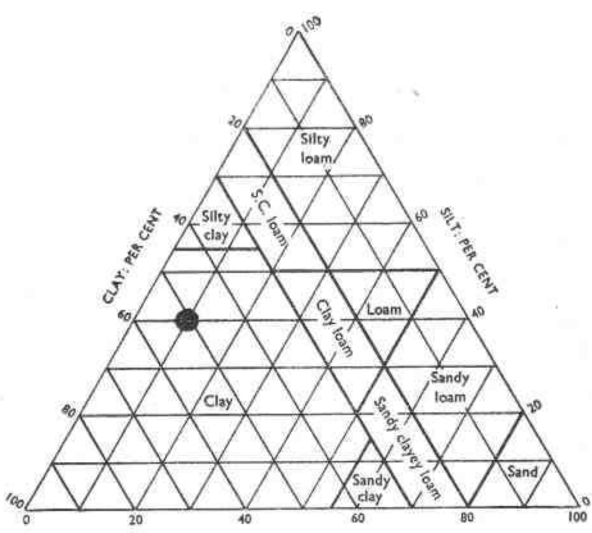

FIG. 16.—U.S. BUREAU OF SOIL. TRIANGULAR CLASS CHART

commonly found in the northern parts of the North American continent. All the points were well above the A-line.

90. Since the natural water content of the soil was well above the liquid limit and would flow, as expected, upon disturbance, Mr Mak wondered how the sensitivity of 4 to 8, as quoted, was obtained.

Mr J. G. Knibb (formerly of the Air Ministry Soil Laboratory) noted that the varved clays, while varying as described, nevertheless seemed to be of a uniform type over a very wide area and to considerable depth. This was very different from his own experiences in "drift" areas.

92. The informal device of assessing the bearing capacity of the ground for an

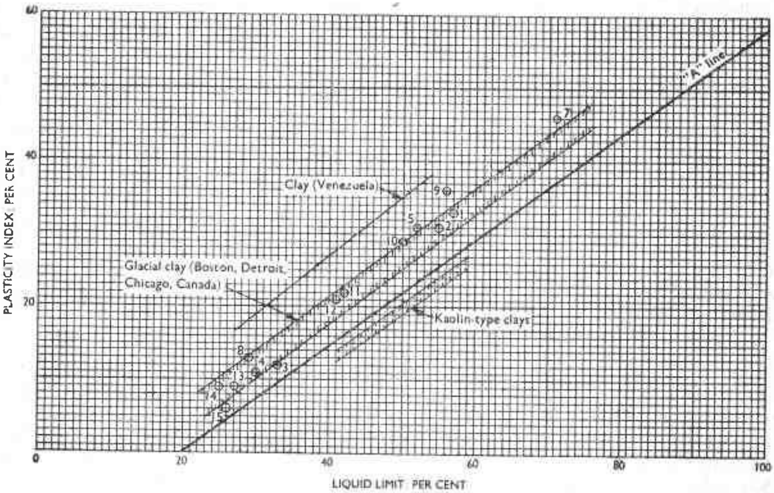

FIG. 17.—PLASTICITY CHART (UNIFIED SOIL CLASSIFICATION)

embankment by using one's own weight on various sized boards was a useful first line attack. The criterion of not permitting slopes exceeding the natural slopes in the district was very handy indeed but was often an oversimplification (although he had used it on at least one occasion himself).

93. Would the Author explain the log in Fig. 9 and would he describe the boring and sampling technique and also the method of making remoulded specimens of silt above the liquid limit?

94. The Paper emphasized the importance of measuring both undisturbed and remoulded soil characteristics if catastrophic failures were to be avoided.

95. Had the passage of time stabilized the slopes by drying of the silt and if not, had thought been given to the effect of an accidental or deliberate explosion in the workings or on the banks?

Dr P. G. H. Boswell (Emeritus Professor of Geology, Imperial College of Science and Technology) observed that the problems that had arisen during the draining of Steep Rock Lake had been in no small measure due to what might still be described as abnormal geological conditions, although it should be noted that in the course of the past 20 years or so, similar conditions had been found to occur more frequently than had been realized. The nature of the bonding forces in fine-grained materials such as silty clays, which largely determined their behaviour, was but little understood: thus, a writer could declare recently in an American publication that their subsequent behaviour in constructional work could not be adequately predicted from empirical laboratory testing. However, the success that had attended the application of geotechnical laboratory data seemed to belie this statement in its generalized form, made though it had been by an expert in the field. The truth of the matter was doubtless that there were soils and soils, and some were more peculiar than others! The glacial silts and the silty bands in the varves described in the Paper as having remarkably low plasticity and notably high natural water content, provided excellent examples of the phenomenon known to physical chemists as thixotropic behaviour, that was, they were gels which were stable and resistant to stress up to their yield points, but became sols (or more fluid gels) and flowed freely on shock. After being allowed to rest, they became rigid gels once more. Their structure had been proved by means of freezing and subliming methods to be a meshwork of solid particles (Mr Legget's honeycomb), in the relatively large cell-like spaces of which the water was retained. Ionic (and in part, possibly, molecular) forces held the structure together. If the natural moisture content was appropriate, most clayey and silty systems were thixotropic, but they were also plastic, so much so that the late Prof. H. Freundlich, who had introduced the term, had spoken of these properties as sympathetic. Why should the Steep Rock and other Canadian silts found by Mr Legget have been only slightly plastic? To say that they were largely composed of rock flour and not of colloidal clay minerals only begged the question. Here was a subject for research.

97. The behaviour of the mud river when the peculiar soil flowed was also worth investigating. Having ceased to flow, did it separate into denser mud and clear water? Or did it take up its original condition as regards water content? Both kinds of behaviour had been recorded but, unfortunately, not in relation to the original index properties of the soils.

Mr F. L. Lawton (Chief Engineer, Aluminium Laboratories Limited) observed that many soils were found in the area which, on first inspection, appeared to be clays but were in reality largely silt or rock flour, resulting from glacial action.

99. A possible material which had been investigated for the impervious core of a rockfill dam in Northern Quebec, had previously been described by the Author[18] in the following terms:

> "When wet it had the appearance of liver and could be handled in thin pieces just as if it were meat! It did not have a clay-like feel but upon testing gave a P.I. of 7·6% and Lower Liquid Limit of 30·8%—possibly due to the extreme fineness of the constituent particles."

100. The Author had commented that the "leathery" feel and appearance of the original sample, as delivered at the laboratory, could be duplicated by adding the correct quantity of water to the dried sample. A significant observation was that while the material would, in practice, probably be impervious it would prove to be very unstable in the presence of any excess of water over the liquid limit, under which circumstances it would run like soup.

101. The Author's observations in § 17 demonstrated the typical characteristics of fine-grained sediments of glacial origin in the Canadian Shield. The use of the criteria derived from a study of the behaviour of the sediments at Steep Rock in the formation of the Hogarth Barrier would appear to be somewhat analogous to the Russian technique of constructing dams by deposition of dredged material, the feasibility of which had been demonstrated indirectly many times in dredging operations throughout the world.

Mr D. H. MacDonald and **Mr T. C. Kenney** (Geotechnical Engineer and Assistant Geotechnical Engineer respectively, Technical Division, H. G. Acres & Company Limited) wrote that the soils which covered a very large portion of Canada owed their origin to the continental glaciations which had extended over much of the northern hemisphere during the Pleistocene epoch. Amongst those soils, which included tills, granular outwash deposits, and post-glacial marine clays, were the deposits known as varved clays. The details of their geological origin were still problematical, and their engineering behaviour was not well understood. Every contribution towards a better understanding of them was welcome.

103. The geological aspect of varved clays, particularly their cyclical method of deposition, had been investigated for many years.[19] The geotechnical properties of the different soil layers in these deposits had received comparatively little attention, while the literature contained almost nothing on the characteristics of greatest value to the practising engineer, namely, shear strength, consolidation, and permeability. This fact could probably be attributed to the difficulties in testing techniques which these soils presented, but it also indicated the direction in which the greatest progress on this problem could be made.

104. The characteristic which distinguished varved clays from other clay deposits was the regular variation in properties within a small portion of the deposit, or the lack of homogeneity on a small scale. This structural feature of varved clays was of fundamental importance and a knowledge of the in-situ variations in properties throughout the soil was a necessity for a clear understanding of their performance. It should be noted, however, that varved clays might be reworked for use in construction, as for example in the rolled-fill core of a dam, but in so doing the variations in properties of the different layers were destroyed and a homogeneous soil was produced. In this condition it might be treated by the accepted procedures and methods of design currently in use for other clay soils.

105. Extra-sensitivity as defined by Skempton and Northey[20] had been encountered in a striking manner in the Steep Rock soils, but since this property was found to a marked extent in the post-glacial marine clays of Scandinavia[21] and Eastern Canada[22] it could not be considered to be solely characteristic of varved clays. Its presence might, however, dictate the adoption of special, and sometimes ingenious, construction techniques as described by the Author and as employed elsewhere in marine clays.

106. Most of the usual design problems arising with other soils could also be encountered with varved clays; these were problems of seepage, settlement, and stability. Since the last was possibly the most important problem requiring attention and since a virtually complete absence of published stability analyses suggested that the mechanism of failure in varved clays was not well understood, it was interesting to speculate on the applicability of conventional soil-testing techniques and methods of stability analysis to varved clays.

107. To predict analytically the performance of a structure a method of analysis, a knowledge of the loading conditions, and a knowledge of the properties of the materials involved were required. In addition, the assumptions inherent in the method of analysis and the conditions for which the properties of the materials were valid must be compatible with the conditions existing in the field. In soil mechanics there were two accepted methods of stability analysis which were applicable to saturated clays:

(i) The $\phi = 0$ total stress analysis, which was used in problems where there was no appreciable change in the water content of the soil as a result of changes in loading. In this analysis the shear strengths of the soil were obtained from undrained tests such as undrained compression tests and vane tests.

(ii) The c', ϕ' effective stress analysis, which was used in problems where the pore-water pressures existing in the field could be measured or estimated. In this analysis the shear strengths were obtained from undrained tests with pore-water-pressure measurements, or from drained tests.

108. The applicability of these methods of analysis and the associated methods of testing had now been well established, and their validity had been confirmed.[23, 24]

109. In principle, these methods of analysis and testing were applicable to all saturated clays, including varved clays. However, in practice, their application to varved clays was complicated by the fact that the soil consisted of layers with different shear strength and stress/strain properties, and so far it had been found difficult to

establish the correct laboratory testing procedure which would reproduce conditions and give strengths which were in agreement with those existing in the field. The problem of predicting stability in varved clays was therefore the determination of the correct shear-strength values by laboratory or field tests for use in the appropriate type of stability analysis. Any method of determining these shear strengths must take into account the following factors:—

(i) *Drainage conditions.*—The drainage conditions of the sample being tested must be such that the test results could be interpreted in terms of the type of stress which was considered in the analysis, and these drainage conditions must be in agreement with those existing in the field. In the case of undrained field conditions, laboratory or field determinations of shear strength must also be made for conditions of no drainage. In the case where changes in water content were taking place, the method of analysis must be with respect to effective stresses and for this reason the strength determinations must be made in such a way that the effective stresses acting within the sample were known, i.e. by drained tests or by undrained tests with pore-water-pressure measurements.

(ii) *Type of failure.*—In the field, failure usually took place along a smooth surface rather than a broken or irregular surface, and the soil everywhere along this surface failed in shear (except, of course, that portion near the ground surface where a tension crack may form). To produce this type of failure in the laboratory or in the field test the failure surface must be made planar. In homogeneous soils a planar type of failure should always occur but in varved clays where the soil properties might change appreciably within short distances the sample might fail along an irregular surface in the process of seeking out the surface of least resistance. It had been shown by Eden[25] that this could occur in the unconfined compression test where samples failed partly in tension and partly in shear. This type of failure was kinematically impossible in the field and therefore the value of any tests which failed in this manner was questionable. Tschebotarioff and Bayliss[26] had shown that in some compression tests on varved clays the weaker layer had squeezed out from between two of the stronger layers. The results of such tests would be a measure of the shear strengths of the weaker layers, but if analysed as a standard compression test the resulting value for the shear strength would represent neither the actual shear strength of the weaker layer nor that of the varved sample.

(iii) *Location of failure surface.*—In Fig. 18 the variations of tan ϕ_d and $\frac{Cu}{p}$ with the plasticity index (P.I.) of normally consolidated clays were shown. It could be seen that the shear-strength properties of the different soils in the layers of a varved clay did vary, especially when they were tested in the undrained condition. If failure took place wholly within one layer, the shear strength mobilized along the failure surface would be expected to equal the shear strength of the soil making up that layer. If, however, failure took place across the layers, it could be shown that, for differing values of the shear strength, strain at failure, and thickness of layer for the two different types of layers, the mobilized shear strength might vary from a value less than the shear strength of the weaker layer to a value greater than the shear strength of the weaker layer, but always less than the shear strength of the stronger layer. It followed, therefore, that the orientation of the failure surface relative to the plane of the varves must be controlled in laboratory or field tests to determine the shear strength.

The shear strength mobilized along a plane surface passing across the layers was probably independent, to a very large degree, of the orientation of the failure surface, except where it became almost parallel to the varves since the relative proportions of the different layers cut by a plane failure surface were dependent solely upon the relative thicknesses of the varves and are independent of their orientation. Eden[7] had concluded on the basis of unconfined compression test results that the strength was dependent upon the orientation of the varves, but the validity of this conclusion was doubtful since it appeared that failure did not always occur entirely by shearing.

110. The test which appeared to satisfy these requirements best was the shear box test, in which the sample failed in direct shear and in which the orientation of the failure plane could be controlled. Some difficulties might, however, be encountered in controlling the drainage conditions satisfactorily in this test. A reasonable testing programme would include drained or undrained tests, depending upon the field conditions,

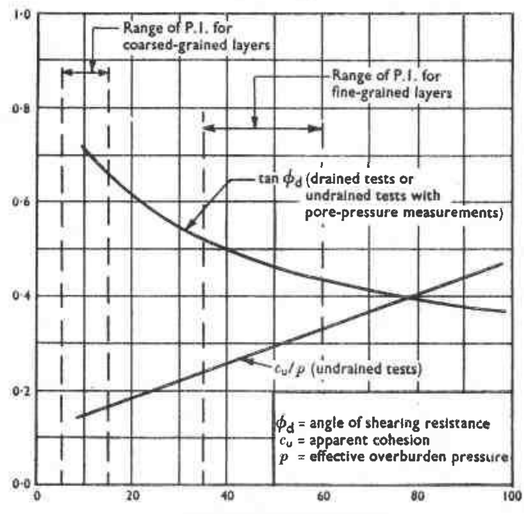

FIG. 18.—RELATION BETWEEN tan ϕ_d, c_u/p, AND P.I. FOR NORMALLY CONSOLIDATED CLAY

in which failure was made to occur completely through the weakest layer and at an angle or perpendicular to the varves.

111. If the shear strengths along a single layer and across the varves had almost the same values, as might be expected for drained conditions (see Fig. 18), the use of a single strength value in the stability analysis was justified. If, however, these values were materially different, as might be expected for undrained conditions, then the different values must be applied to the appropriate portions of the assumed failure surface in the analysis.

112. It was interesting to note that the extra-sensitivity of some soils, including those encountered at Steep Rock, did not cause initial instability, and for this reason it was not considered in any stability calculations. However, when failure has occurred remoulding of the sensitive soil will take place and it will flow away from the exposed slope, thus removing from it a potential stabilizing mass. This might indirectly contribute to additional sliding in the exposed slope.

113. There were at the present time extremely few published data relevant to the shear strengths and consolidation characteristics of varved clays and to the suitability of conventional analyses for stability problems involving them. A consideration of the problem seemed to indicate that there was no reason to believe that the present methods of analysis would not be satisfactory if the correct values of shear strength

were used. The determination of the latter and their use in the analysis of actual slope or foundation failures appeared to offer the greatest scope for fruitful work towards the solution of this interesting and important problem.

Mr N. D. Lea* (Engineering Division, Foundation of Canada Engineering Corporation Ltd) referred to the Author's comprehensive description of the characteristics of the materials involved and of the tests performed on them. He suggested that thixotropy would provide a further useful avenue of investigation. He had observed that materials whose natural moisture content was above the liquid limit were also frequently thixotropic. It might be that that phenomenon could be used to explain some of the Author's observations. The angle of shearing resistance observed in the tests, which Mr Lea believed had been unconsolidated and undrained, was low (it could normally be expected to be zero) might in some way be related to the thixotropic properties.

115. The properties of varved clays were naturally difficult to study, for separation of the layers left such small quantities. There had been some painstaking research done in slicing the material into individual layers and some useful results had been obtained. The Foundation Corporation had used another technique, however, which he thought might be useful for further research: in all the routine testing, whether of moisture content, or limits, strength, or consolidation, they observed carefully and recorded the percentage of each of the light and dark materials involved in the test for each moisture content. Then when a long series of results had been accumulated it was possible to plot them against the percentage of light and dark varves. On many projects the plot had resulted in a straight line for the moisture content, the liquid limit and the plastic limit. These results could be extrapolated back to the zero ordinate to give the specific value pertaining to 100% light material or to the 100% ordinate to give the value pertaining to 100% dark material. When interpreting the shear strength results it was important that the percentage should be only the percentage on the shear plane of failure, not the percentage of material in the whole sample.

116. It was important to be as specific as possible when describing varved materials. The terms "silt" and "clay" seemed to be used indiscriminately. The Foundation took care to distinguish between them, and sometimes, when materials were mixed, found it necessary to distinguish between "varved silt clay" and "varved silt and silty clay". The difference in properties was often quite noticeable, even in a small sample.

Dean R. M. Hardy (Faculty of Applied Science, University of Alberta, Edmonton, Canada) remarked that while the experience of Steep Rock Iron Mines had been made available to Caland Ore Company (to whom the "C" ore body had been leased), there were still major problems involving soil engineering on the Caland project. The most important of these arose from the fact that the "C" ore body had been overlain by as much as 400 ft of varved clay. This had required consideration of the safe slope in this material for a vertical height of 400 ft as compared with the maximum height of 160 ft in the Steep Rock Iron Mines development. A second major problem had arisen, because substantial economies were possible if certain of the dams could be built on a foundation of the varved clay.

118. The Caland project[27] had involved the pumping of about 2,000,000,000 gallons of water and the dredging of approximately 150,000,000 cu. yd of varved clay from the Falls Bay area of Steep Rock Lake (see Fig. 2b, p. 173). The main disposal area for the dredged material and source of re-charge water was Marmion Lake, which was part of the drainage basin of the Seine River, and it had therefore been necessary to cut off its flow, except during periods of flood flow, by dams. In addition to the dredging operation the development had required the construction of twenty earth dams and

---

* This and the following three contributions were made orally at a Joint Meeting of the Saskatoon Branch of the Engineering Institute of Canada and the Association of Professional Engineers of Saskatchewan, at Saskatoon, on 8 December, 1958.

dikes. Construction work had commenced in 1954 on a schedule providing for the first commercial production of ore in 1960 and full production in 1969.

119. The most interesting of the dams from the soil mechanics point of view was the Fairweather Dam across the mouth of the "south-east arm" of Falls Bay at the south-east end of the "C" ore body (see Fig. 2b, p. 173). This structure had a maximum height of 80 ft and was built on a foundation of varved clay varying in thickness to a maximum of 70 ft. It was a rolled-fill dam, having a homogeneous cross-section and built of glacial till material with both upstream and downstream slopes averaging 1 to 5. About 600,000 cu. yd of material had been placed in the embankment fill and it had been built in three stages extending over the 1955–57 construction seasons.

120. The south-east arm of Falls Bay had been drained by the Steep Rock Iron Mines dredging operations in 1944 and therefore the varved clay had been consolidating under increased total stresses for a period of about 10 years previous to the construction of the dam. Consolidation tests on twenty samples of the subsoil at the dam site had shown an extraordinarily wide range of compressibility, with initial void ratios ranging from 0·55 to 2·45 and compressive indices from 0·1 to 1·5. These characteristics appeared to vary almost at random and precise values could not be assigned to specific continuous soil zones.

121. The most unfavourable values for soil characteristics from the tests had indicated that total settlements of several feet might develop and that difficulties might develop with foundation stability with any practical side slopes. On the other hand, using average values of the soil characteristics it had appeared quite possible to build safely on the varved clay. These factors had dictated that, if the dam was to be built, the performance of the foundation soil would need to be assessed as the structure was built, and further that it should be built in stages to permit advantage to be taken of the increase in strength of the foundation soil arising from consolidation previous to the application of the full load on the subsoil.

122. Seventeen settlement gauges had therefore been installed at the bottom of the embankment fill and nine piezometers had been placed in the varved clay forming the dam foundation, all for the purpose of assessing the performance of the subsoil during the various stages of construction of the dam. The structure had been completed in 1957 and its performance to date had been completely satisfactory. A railroad would be built across the dam in 1959.

123. The most difficult problem with the stability of dredged slopes in the varved clay had been concerned with the material in the east arm. From the "C" ore body in Falls Bay south into the east arm a stable slope in the varved clay had been required for a vertical rise of 400 ft. The soil investigations for the Steep Rock Iron Mines project had not shown a significant increase in shearing strength with depth for the varved clay. In view of the comparatively great depth of the material involved in the Caland project it had been of considerable economic importance to establish, for certain, what variation in strength with depth existed. This had not been a simple problem because it had proved to be impossible to secure reliable undisturbed samples at depths of even as much as 100 ft, owing to the high sensitivity of the varved clay. In-situ vane tests had finally been resorted to, and these had indicated a ratio of shearing strength C to submerged weight of overburden P of from 0·35 to 0·40. An overall slope of 1 to 6 had been finally selected.

124. The finally designed safe slope allowed only for stability against a deep-seated slide. It did not take into consideration stability against shallow surface flow slides. The Author had pointed out that a considerable yardage of dredged clay from the west arm had been pumped into the east arm during the early operations of Steep Rock Iron Mines. The stability of this re-deposited material had been unknown. All that had been known was that flow slides could result from draw-down of the lake. Actually during 1955, 1956, and 1957 six flow slides had developed in the east arm, involving a movement of a total of about 5 million cu. yd. Some of these slides had developed on slopes as flat as 1 in 28; they had involved mostly re-deposited material, but the movements appeared to have extended to shallow depths into original soil.

125. An analysis of these six flow slides had led to an empirical relation between rate of draw-down and duration of draw-down that resulted in a slide developing. This empirical data had been used in designing the 1958 dredging programme with complete success. No draw-down slides had occurred in 1958.

126. It was interesting to speculate on the reasons for the peculiar properties of the varved clays. There was some evidence that their high natural moisture content in relation to their liquid limits and their high sensitivity were the result of extraordinarily rapid increase in thixotropic bonds when the individual particles came in contact with one another.

127. Fig. 19 had been sketched from a photograph of a boulder about 8 in. dia., which had been exposed in the dredging operations in Falls Bay. It was an isolated boulder in a mass of varved clay extending for many feet both above and below it.

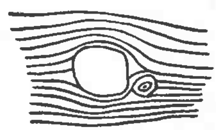

FIG. 19

Presumably the boulder had been dropped from ice on the lake surface. The distortions to the varves around the boulder suggested several interesting conclusions concerning the build-up of strength in the clay. In coming to rest on the clay the boulder had not even displaced its own volume in the clay. It therefore followed that the surface layers of the clay had had an appreciable shearing strength and this build-up of strength must have been quite rapid. It would also be noted, however, that the weight of the boulder had compressed or consolidated the soil for several inches below the surface where it had come to rest. It was interesting that subsequent consolidation of these same varves due to the weight of many feet of overburden had not been as great as had been caused by the weight of the boulder. This could only mean that a substantial increase in particle bond strength and therefore a reduction in compressibility had occurred in the interval between the time of deposition of the boulder and the completion of the deposition of the lake bed deposit. The steep slope of the surface of the first varve deposited on top of the boulder was also a positive indication of a rapid build-up of stability at the time of deposition.

128. A rapid build-up of thixotropic forces could account for natural moisture contents exceeding the liquid limit and also a high degree of sensitivity.

Mr C. F. Ripley (Ripley & Associates, Engineering Consultants, Ltd, Vancouver, B.C.) observed that similar problems of superficial instability of cut slopes due to to surface gullying, internal piping, and flow slides were encountered in the coastal area of British Columbia. Because of high relief in that area, many of the plant-site developments involved substantial excavations into stratified deposits of sand, silt, and clay to form flat-lying areas or benches on which the plant could be founded. Most of these deposits were interglacial and had been preconsolidated by ice loads. They were generally stiffer and had lower water contents than those mentioned by the Author. They therefore had high shear strength and generally stood at much steeper slopes (1 in 1½) for heights up to 100 ft without shear failure. However, because of the high annual precipitation in the area, which ranged from 40 in. to 180 in. within a distance of 25 miles from the Fraser River delta to the mountain valleys, the superficial instability problem was very severe. Could the Author give the average precipitation in the Steep Rock area for comparison?

130. The same general principles used by the Author in protecting the cut slopes at Steep Rock were also successful in British Columbia for the conditions described above. Careful control of surface drainage was essential to remove rain-water falling on the slopes and to intercept all surface-water from adjoining off-site areas. It was found that the steeper the slopes could be constructed, commensurate with general stability requirements, the smaller was the catchment area for rain-water and the less severe the erosion problem.

131. Piping problems were also severe, because of hydrostatic conditions in granular layers and pockets in the deposits resulting from the heavy rainfall and high topography. Where these occurred, they were handled directly at their point of emergence from the slope, by means of select granular filters and metal offtake pipes.

132. On the basis of experience it had been found essential that protective cover be provided for the slopes prior to the onset of the wet winter season; otherwise severe damage of the unprotected erodible soils occurred. For this purpose granular blankets and/or vegetative covers were used. It had also been found that berms, as discussed by the Author, were required to control superficial instability rather than overall slope failure. The berms furnished access to steep slopes for construction and maintenance equipment, provided collection points for drainage water, and also provided bases on which the blankets could be founded.

133. An additional point of technical interest and of significant practical application mentioned by the Author, was the use of a 4-ft-thick granular fill for access roadways across the soft lake deposits. The Author has indicated that his decision concerning the required thickness of 4 ft for support of vehicles had had to be made in a hurry without benefit of a detailed analysis. It was therefore interesting to note from experience with soft soils in British Columbia, that a detailed investigation made of the performance of a paved roadway subjected to the same Euclid vehicles had indicated that a minimum thickness of 3–4 ft was required to support the unusually heavy 25-ton axle loadings of the Euclid vehicles over very soft organic terrain. This confirmed the soundness of the decision that the Steep Rock soft lake deposit could be traversed by such heavy vehicles using a 4-ft-thick granular base. Further confirmation of the fact that very soft ground could be traversed by heavy vehicles, using a comparable thickness of base, was the published experience at Logan Airport in Boston,[28] where a 5-ft-thick base had been selected for support of heavy aircraft wheel loads above a deposit of soft dredged clay fill.

Dean A. E. MacDonald (University of Manitoba, Winnipeg), referring to § 5, observed that a great deal of difficulty had been experienced in freeing the frozen iron ore from the bottom-dump railway cars after their arrival on the unloading dock at Port Arthur. How had this difficulty been finally overcome? Were the production figures given in § 6 in long or short tons?

135. He had noted from § 9 that slides had been caused by drawdown in the water level disturbing the natural equilibrium and by internal erosion of the material at the toes of the slopes. In Winnipeg, it was the custom each autumn to open St Andrew's Locks on the Red River for the winter months, which lowered the levels of both the Assiniboine and Red Rivers for this period, and then to close the locks in the spring, which raised the water levels for the summer months. This procedure was repeated year after year and, since the river banks were largely of varved clays, slides frequently occurred. Here there would seem to be stability problems not wholly unlike those encountered at Steep Rock Lake, for which the solution might be man-made vegetation-covered berms and rises which Nature herself sometimes provided.

136. Why had not the suction dredges (§ 39) been equipped with rock catchers? Would the cost and inconvenience of using rock catchers have outweighed the loss of the 1,910 hours of pumping time?

The Author, in reply, thought it was unfortunate that Mr Ward had concluded that the exposure which he described (§ 73) was "typical" in view of his extensive knowledge of glacial phenomena and well-known accuracy of observation, since it was, in fact, unique to the location available for inspection at the time of Mr Ward's visit. Careful checks, since the presentation of the Paper, with others who were familiar with the Steep Rock operation had confirmed the Author's impression that at least 95% of the lake-bed deposits (and probably an even higher percentage) were grey varved clays as generally described in the Paper. Mr Ward's description was, however, interesting and valuable as indicative of the character of the deltaic deposits formed at the inflow to the glacial lake during the formation of some, at least, of the lake-bed deposits. The location was far removed from the entry of the Seine River to the lake in modern times. No similar deltaic deposits had been observed anywhere around the 20 miles of shoreline of that part of the lake which had been emptied.

138. Professor Skempton had asked for a cross-section through the lake. The development of the mine, although requiring a great deal of deep drilling, had not called for any drilling programme extending fully across any section of the lake and it was for that reason that the Paper did not include such a cross-section as an illustration. Fig. 20,

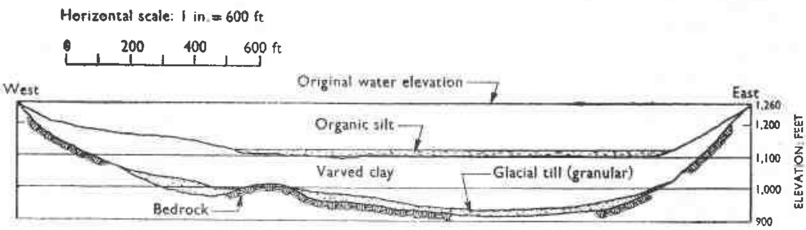

FIG. 20.—APPROXIMATE SECTION THROUGH STEEP ROCK LAKE AT THE HOGARTH BARRIER BEFORE DREDGING

which repaired the omission, included a fairly accurate section at the narrow part of the Middle Arm utilized as the location of the Hogarth Barrier, based upon such dimensions as were readily available.

139. Much interest had been shown in the properties of the varved clays and in the test results so briefly reported in the Paper. Some of the questions relating to soil properties had been answered in the discussion, the presentation by Dr Cooling of a summary of his own test results being particularly helpful in this connexion. Dr Cooling's confirmation of Mr Eden's suggestions of montmorillonite in the dark layers, for example, answered Professor Skempton's comment on this point (§ 51).

140. Answers to almost all the remaining questions about soil properties could be found in reference 9. Eden's detailed laboratory studies were being continued and it was hoped that a record of further results of his work would soon be published.

141. The scope of the mining operation was so vast, and the urgency of the initial development because of the imperative of war had been so great, that all the original (and therefore major) decisions regarding the handling of the soil problems had had to be made on the basis of extremely limited information on soil properties, obtained from the simple test-boring programme described (§ 16). The varved character of the soil samples had been merely noted at that time (§ 52) but its scientific significance had not been fully appreciated until time had finally permitted a more careful examination of remaining soil samples; by that time excavation had been well advanced and the varved soil structure had also been observed in situ. The detailed soil studies, as reported by Eden and as considered in the discussion, were a relatively recent "scientific by-product" of the Steep Rock operation. They constituted a continuing research challenge, which

the Author and his colleagues were attempting to meet, consistent with their other responsibilities.

142. In view of the interest in soil properties expressed in the discussion, the Author particularly regretted the omission of a legend to Fig. 9 (p. 177). The log showed the natural moisture contents (open circles), the water plasticity ratio (blacked circles), and the liquid and plastic limits (the ends of the bar markings). Dr Cooling's observations regarding the differing value of liquid limits for air-dried and for natural samples (§ 58) were interesting: Eden had found, however, liquid limits of natural samples of the dark and light varves to be exceeded by the natural moisture contents.

143. Paradoxical though it might be (§ 50) the strength of the lake-bed deposits did not appear to increase with depth, to the depths studied in the original Steep Rock investigations (about 150 ft). Dean Hardy, in his corresponding studies, for the Caland part of the project, had found some evidence of increase at great depth (§ 123) but the use of in-situ vane tests for this determination still left the matter in some doubt. The existence of varves probably tended to screen any slight increase, especially since the varves sometimes increased in thickness with depth. Macdonald and Kenney had provided useful comment (§§ 100 *et seq.*) on this matter.

144. In answer to Mr Knibb (§ 93) soil sampling had originally been carried out by the wash-boring of holes, and undisturbed samples had been procured by using split-tube samplers forced into the soil at the bottom of such holes. In more recent studies, continuous soil samples had been obtained in Shelby tubing. Remoulded samples (§ 93) had been formed in the usual way, this being possible because of the loss of free water upon disturbance of the soil, the remoulded soil thus inevitably having an actual moisture content less than when the sample was removed from the ground. This comment related also to Professor Boswell's question (§ 97), the masses of soil that did move always "hardening up" quite rapidly and behaving thereafter as "ordinary" silt or silty clay.

145. Soil sensitivity (§ 90) had been determined by the use of a small laboratory vane tester; the results were given in some detail in reference 9.

146. The passage of time had undoubtedly seen a progressive increase in the stability of the slopes, as suggested by Mr Knibb (§ 95) and inferred by Mr Sutherland (§ 84). Because of this, no modifications had had to be made to slopes, once they had been formed as described in the Paper, until such time as complete removal of the sloped soil had been carried out. No blasting had been used, therefore, in connexion with stability of slopes in the varved clay, although a great deal of blasting had been carried out in connexion with the open-pit mining operations. In spite of occasional very heavy blasting (using up to 20 tons of explosive in one shot), no slope failures had been caused by the consequent vibrations.

147. The mechanism of the flow slides had been questioned in §§ 49, 61, and 85. The Author's appreciation of these unusual soil movements could certainly have been better expressed. In further explanation, therefore, it should first be noted that no "analysis" of any of the early soil movements could be made, as requested by Professor Skempton, since none of them had assumed any regular form, being always of the character of flows such as that illustrated in Fig. 5. The statement in § 20, quoted by Dr Cooling in § 61, was certainly a terminological inexactitude since "the strength of the soil in place" was clearly the summation of the strengths of the various component parts of the soil, i.e. of the individual varves. What had been in the Author's mind when writing this misleading statement, was the fact that all the flow slides which he had seen at Steep Rock had been started by a major interference with an apparently stable slope, e.g. by the removal of soil at the toe of the slope, either by excavation or by erosion due to uncontrolled drainage, leading to a collapse of the unstable face then formed and almost instantaneous "liquefaction" of the mass of soil thus affected.

148. The pointed and interesting questions about the process of varve formation (§§ 53, 63, 64, and 96) touched upon a fascinating problem in geological theory. The Author regretted that he could not attempt to interpret Dr Antevs's extensive Paper to Mr Kellaway, even though he had had the unique privilege of being with Dr Antevs

when starting his detailed field studies of the Steep Rock varves. Nor did the Author wish publicly to dispute the well-accepted theory of De Geer, mentioned by Professor Skempton. Since, however, Dr Antevs himself had been unwilling to accept fully the findings of carbon-14 dating techniques in relation to varved soils,[29] it might not be too presumptuous for the Author to admit to a slight degree of the scepticism to which Professor Skempton had so guardedly referred.

149. The Author and his colleagues had considered with open minds the results of their engineering soil studies, and their field observations of the great deposits in the bed of Steep Rock Lake, so clearly varved. They appreciated the beauty of De Geer's theoretical explanation but they found themselves unable to fit some of the things they had seen into the simple theory. At the same time, it had to be admitted (in answer to Professor Skempton) that the time scale of varve deposition must be at least approximately that suggested by the De Geer theory. Questions arose rather in connexion with the actual process of deposition.

150. Since the Paper was a summary of the civil engineering aspects of the Steep Rock project, it would not be appropriate to go further into this geological problem in this reply. Those who wished to study the matter further would find a statement of some of the Author's questions about varving in reference 8, and further relevant information in reference 9.

151. Mr Little had requested (§ 68) some further information regarding the operation of the large dredges. Bennett[10] had given reasonably complete information about the dredging contracts, and the operation of the dredges. The Author would hesitate to extrapolate the excavation experience at Steep Rock to the case mentioned by Mr Little, especially since difficulties had been experienced with the use of hydraulically placed fill in some large earth dams. If the soil properties were suitable, however, and if the economics of the particular job favoured hydraulic methods (as they did at Steep Rock), then the experience at Steep Rock could be of value as showing what could be done, in respect of the volume and time, by this method of excavation.

152. In reply to Mr Little's further query (§ 68), the choice of a single very large dredge, as compared to several smaller designs, had again been a matter of economic assessment. The latter course was naturally a more flexible arrangement; the advantages of flexibility should be compared with the economic advantage of the large single machine. Rock catchers, as Dean MacDonald had suggested (§ 133), would have been of great service but their necessity had become evident only when the dredges were in use and it was too late to change their design.

153. The Author agreed entirely with the detailed assessment presented by Dr Macdonald and Mr Kenney (§§ 102 *et seq.*). He would like to repair another omission in the Paper, however, by recording that the extensive preliminary civil engineering works (§§ 3, 4) were designed by H. G. Acres & Company of Niagara Falls.

154. Details of the boulder found in the varved clay by Dean Hardy served to confirm some of the Author's questions about the deposition of varved material.

155. In answer to Mr Ripley (§ 129), annual average precipitation at Atikokan (5 miles to the south of Steep Rock Lake), was 24·12 in., so that rainfall was not a "problem" on the Steep Rock job. It was a tradition of the iron-ore-shipping industry on the Great Lakes (in answer to Dean Macdonald (§ 134)) that shipments should be measured in long tons; this should have been mentioned in the Paper.

156. Research problems would remain long after the excavation work was complete. The continued support which Steep Rock Iron Mines Ltd had given to the use of the Steep Rock soils as a subject for research was evident from the Paper; the discussion would serve to encourage the Author and his colleagues to avail themselves as fully as possible of the continuing opportunity for further research so generously provided by this mining company.

References

13. T. W. Lambe and R. T. Martin, "Composition and engineering properties of soil". Proc. Highw. Res. Bd., vol. 32 (1953), p. 576.
14. Sir H. T. de la Beche., geological observer, 2nd edn, 1853, p. 42.
15. Ph. H. Kuenen, "Mechanics of varve formation and the action of turbidity currents". Geol. Fören. Förhandl., vol. 73 (1951), p. 69.
16. K. Terzaghi and R. B. Peck, "Soil Mechanics in engineering practice". Wiley, New York, 1948.
17. D. W. Taylor, "Stability of earth slopes". J. Boston soc. civ. Engrs, vol. 24 (1937), p. 197.
18. R. F. Legget and F. L. Peckover, "Notes on some Canadian silts". Proc. Second International Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 1948, vol. 3, p. 96.
19. R. F. Flint, "Glacial geology and the Pleistocene epoch". Wiley, New York, 1947, p. 391.
20. A. W. Skempton and R. D. Northey. "The sensitivity of clays". Géotechnique, Lond., vol. 3 (1952), p. 30.
21. L. Bjerrum, "Geotechnical properties of Norwegian marine clays". Géotechnique, Lond., vol. 4 (1954), p. 49.
22. G. G. Meyerhof, "The mechanism of flow slides in cohesive soils". Géotechnique, Lond., vol. 7 (1957), p. 41.
23. A. W. Skempton, "Opening Address of the European Conference on the Stability of Earth Slopes", Stockholm, 1954, Proc., vol. 3, p. 16.
24. L. Bjerrum and B. Kjaernsli. "Analysis of the stability of some Norwegian natural clay slopes". Géotechnique, Lond., vol. 7 (1957), p. 1.
25. W. J. Eden, "A laboratory study of varved clay from Steep Rock Lake, Ontario". Amer. J. Sci., vol. 253 (1955), p. 659.
26. G. P. Tschebotarioff and J. R. Bayliss, "The determination of the shearing strength of varved clays and their sensitivity to remoulding". Proc. Second International Conf. on Soil Mechanics and Foundation Engineering, Rotterdam, 1948, vol. 1, p. 203.
27. P. D. Pearson, "The Caland Project at Steep Rock Lake". J. Engng Inst. Can., vol. 40 (1957), p. 1657.
28. A. Casagrande, "Soil mechanics in the design and construction of the Logan Airport". J. Boston Soc. civ. Engrs, vol. 36 (1949), p. 192.
29. Ernst Antevs, "Geological tests of the varve and radio-carbon chronologies" J. Geol., vol. 65, p. 129 (Mar. 1957).

A list of all publications of the Division of Building Research is available and may be obtained from the Publications Section, Division of Building Research, National Research Council, Ottawa, Canada.