Paper No. 6304

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

by

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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 ₂ O and CO ₂ free material (ignited)				
SiO ₂ . . .	58.32	66.20	59.05	65.10
Fe ₂ O ₃ . . .	7.35	5.66	5.80	5.10
(Total) (iron)				
Al ₂ O 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 ₂ O ₃ . . .	0.13	0.07	0.09	0.07
Na ₂ O . . .	2.55	3.49	2.94	3.45
K ₂ O . . .	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 Martin¹³ 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 Beche¹⁴ 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 Peck¹⁶ 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 Peck¹⁶ 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 Adesco 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 Author¹⁸ 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 Northey²⁰ 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 Scandinavia²¹ and Eastern Canada²² 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 Eden²⁵ 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. Tschobotarioff and Bayliss²⁶ 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 $\tan \phi_d$ and $\frac{C_u}{p}$ 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. Eden⁷ 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 $\tan \phi_d$, 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 project²⁷ 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 surface gullyng, 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 (blackened 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 Antevis 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. Bennett¹⁰ 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.

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