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The Geotechnical Properties of Impervious Fill Materials in Some Canadian Dams

Les propriétés géotechniques des matériaux du remblai imperméable de quelques barrages canadiens

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Summary

Since 1945 increasing use has been made in Canada of earthfill and rockfill dams. A variety of materials have been used for impervious fill in these dams, and a comparative review of the geotechnical properties of such soils from twenty-five of these dams is included in this paper. In the selection of the dams an attempt has been made to illustrate the several soil types used, to include the major earthfill and rockfill dams now completed, and to provide as complete geographical coverage as possible. The collected data indicate a correlation between the types of soils generally used for impervious fill in the different parts of the country with the nature of the underlying rock and the effects of the Pleistocene glaciations. Approximate ranges of values of the important geotechnical properties, particularly Φ', for the several groups of soils are also discernible, and these may be of some assistance in the preliminary design of these types of dams.

Sommaire

Depuis 1945, au Canada, l'usage des barrages en enrochement ou en terre s'est de plus en plus répandu. Différents matériaux ont été employés pour le remblai imperméable de ces barrages et cette communication comprend une revue comparative des propriétés géotechniques des sols dont on s'est servi dans vingt-cinq d'entre eux. Les barrages ont été choisis avec intention afin d'illustrer les différents types de sols employés, d'inclure les barrages en enrochement ou en terre les plus importants qui aient été construits jusqu'à maintenant et de couvrir une étendue géographique aussi complète que possible. La compilation de ces renseignements montre une corrélation entre les types de sols généralement employés pour les remblais imperméables dans les différentes parties du pays, et la nature de la roche du sous-sol ou les effets des périodes glaciaires du Pléistocène. Les limites approximatives des valeurs des propriétés géotechniques importantes de ces différentes sortes de sols, en particulier la valeur de Φ' peuvent aussi en être déduites et ces valeurs peuvent être utiles lors des études préliminaires aux projets de ces types de barrages.

In the years preceding 1945, few earthfill or rockfill dams were constructed in Canada, and those that had been built were of comparatively small height. Since 1945, however, increasing use has been made of these types of dams and their sizes have progressively increased. At present, the highest earthfill dam is the 200-foot high St. Mary Dam in Alberta, and the highest rockfill dam is the 317-foot high Kenney Dam in British Columbia. The trend toward greater use of these structures is continuing and the heights of several proposed dams would rank them amongst the larger of their types in the world. As dams of these types depend for their economy upon the local availability of suitable construction materials, and because the impervious fill is perhaps the most important element in such dams, it is believed that a comparative review of impervious fills used throughout Canada will be of considerable interest at this time. Many of the data presented in this paper have been collected by the authors while working on the soils of a number of damsites throughout Canada, but, in order that the review will be typical with regard to both geography and the larger dams of the various types now being built, the collected data have been supplemented by additional information either previously published or otherwise made available to the authors.

Geological Considerations

Canada can be divided into four main physiographic and geological regions, distinguished by variations in topography, rock types, and geologic structure [14]. These regions, which are shown in Fig. 1, are the Canadian Shield, the Appalachian Region, the Plains Region, and the Cordilleran Region. The Canadian Shield, which forms an area of approximately 1,770,000 square miles in the northern and eastern parts of the country, is a peneplained region comprised of igneous, metamorphic, and lesser amounts of sedimentary and volcanic rocks, all of Precambrian age. At its southerly and westerly border, these Precambrian rocks dip beneath the gently folded sedimentary rocks of Paleozoic and Mesozoic age which constitute the Plains Region. The sedimentary rocks are shales, limestones, and sandstones, of considerable thickness. The largest area of the Plains Region is the Interior Plain which joins the Cordilleran Region whose mountainous topography was produced by several orogenies in Mesozoic and early Cenozoic times. The Cordilleran rocks consist of deformed sedimentary and volcanic rocks, intruded by immense quantities of igneous rocks.

The Appalachian Region adjoins the eastern border of the Canadian Shield and that part of the Plains Region known as the St. Lawrence Lowlands. It is a region of mountains which were created in Paleozoic times, subsequently eroded and then uplifted to form the present area of moderately low relief. The rocks are a complex assemblage of sedimentary and volcanic rocks accompanied by lesser amounts of igneous and metamorphic types.

During the Pleistocene Epoch, almost the entire area of Canada was subjected to several continental glaciations,

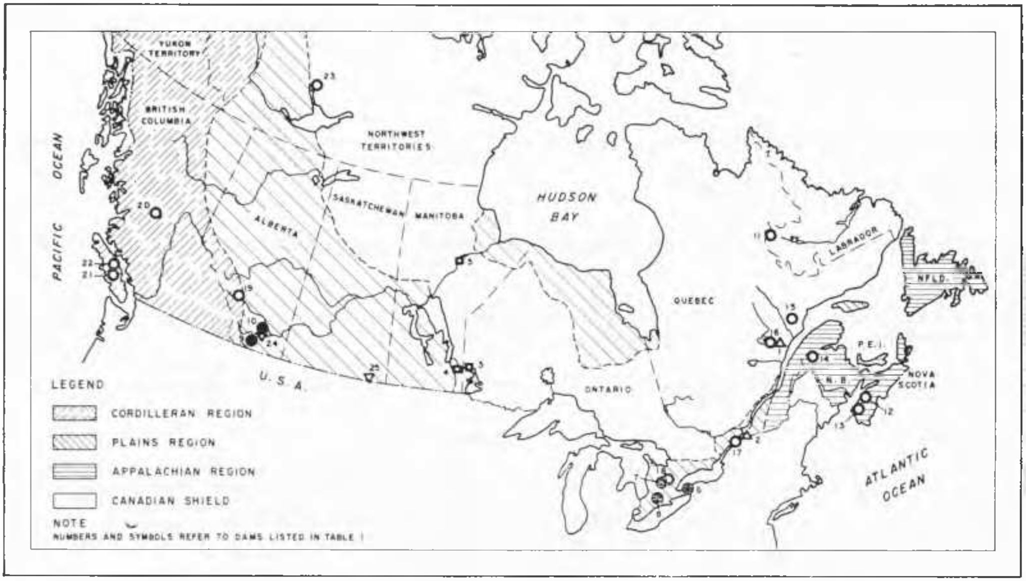

Fig. 1 Locations of Dams in Canada With Respect to the Major Physiographic Regions.
Emplacement des barrages au Canada et principales régions géographiques.

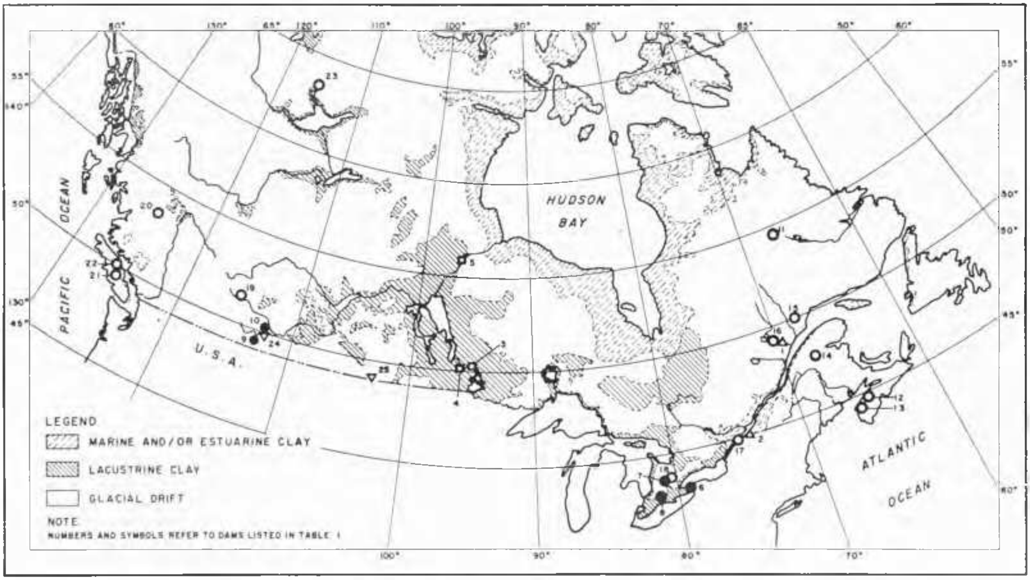

Fig. 2 Locations of Dams in Canada With Respect to the Distribution of Dominant Surface Soil Groups.
Emplacement des barrages au Canada et répartition des groupes dominants de sol de surface.

with the result that most of the present surface overburden deposits are glacially derived either directly or indirectly [7]. During the latest glaciation, the Laurentide ice sheet covered the entire country east of the Cordilleran Region. It originated in, and moved outwards from, several centres, the two main ones being in Central Quebec and in the Northwest Territories just west of Hudson Bay. Minor centres were located in Northern New Brunswick, Newfoundland, and Baffin Island. The Laurentide ice sheet, during its period of maximum extent, abutted the Cordilleran ice sheet along a line approximately coinciding with the boundary between the Plains Region and the Cordilleran Region. The Cordilleran ice sheet originated in the mountainous area of British Columbia and spread outwards in easterly and westerly directions. Two areas of moderate size were not covered by ice, a part of the Yukon Territory, located along the Alaska boundary, and a number of the outermost islands of the Arctic Archipelago.

During the advance and retreat of the glaciers, the bedrock surface and most of the then existing overburden, were either eroded or reworked and subsequently deposited as unsorted glacial drift and water-sorted glacial outwash deposits. Much of the country is now covered with such materials (see Fig. 2). As the glaciers waned, freshwater lakes such as the extinct Lake Agassiz in Manitoba, the extinct Lake Barlow-Ojibway in Northern Ontario-Quebec, and the immediate areas surrounding the larger present-day lakes such as the Great Lakes, were formed. Marine incursions also occurred at this time, particularly in the Hudson Bay Lowlands, and along the St. Lawrence River Valley. Marine and estuarine conditions prevailed in these areas and sedimentation of fine-grained soils produced the well-known marine and estuarine clays.

Because of the extensive glaciation during Pleistocene times, and the temperate climate which has since prevailed in Canada, almost no production of residual soils has occurred. Aeolian soils are also virtually non-existent.

Impervious Fill Materials :

Amongst the group of soil types outlined above those that would be expected to be suitable for impervious fill because of permeability, shear strength, and placing properties, would be the well-graded and more plastic glacial tills, and to a lesser degree the marine, lacustrine, and estuarine clays. To illustrate the use which has been made of these several soil types in dam construction in Canada, data have been collected from twenty-five dams which were selected as being representative of (a) the largest earthfill and rockfill dams constructed in Canada (hydraulic-fill dams excluded), (b) the types of soil most probably available in the various regions of the country, and (c) the variations in types of soil used in Canada for impervious fill in dam construction. The pertinent data concerning these twenty-five dams and the impervious materials used in them are contained in Table 1.

The dams in Table 1 have been grouped as shown according to soil type, and it is not surprising, in view of the widespread occurrence and satisfactory properties of the glacial tills, that they have been used in eighteen of the twenty-five dams. Considerably less use has been made of the marine, estuarine, and lacustrine clays, while residual soils would appear to have been used even less. Chin Dam in Alberta is the only one of this last type included in Table 1. Boundary Dam has been included to illustrate a rare example of an impervious fill obtained from soft siltstone and sandstone. The geotechnical properties of the several soil types are shown in Table 1 and Figs. 3 and 4, and are briefly described below.

Group A in Table 1 contains one marine clay, Beauharnois No. 3, and one estuarine clay, Bersimis No. 2, both from the St. Lawrence Valley. These two soils have clay fractions ranging from 30 per cent to 60 per cent, are moderately plastic, highly impermeable, and have optimum water

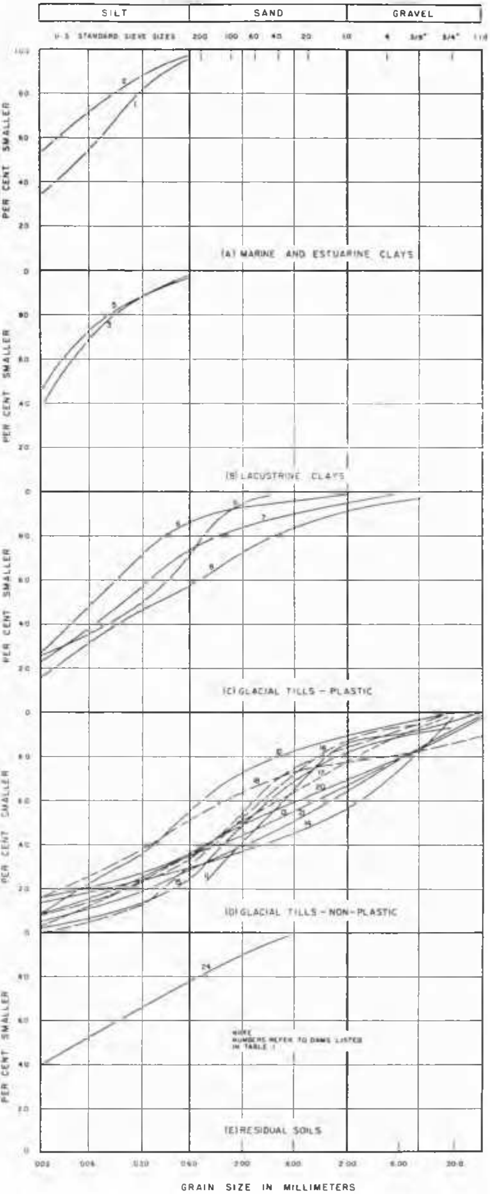

Fig. 3 Grain Size Distribution Curves for Impervious Fill Materials in Canadian Dams.

Granulométrie des matériaux du remblai imperméable dans les barrages canadiens.

TABLE 1 GEOTECHNICAL PROPERTIES OF IMPERVIOUS FILL MATERIALS IN CANADIAN DAMS

NO	DAM OR DYKE		IMPERVIOUS FILL MATERIAL								REF$^{(e)}$
							SHEAR STRENGTH		PLACING CONDITIONS		
							AT WOPT	AT 125% OF WOPT		AV. FIELD COMP'N	
	NAME YEAR OF COMPLETION	TYPE$^{(a)}$ MAX. HEIGHT (FT.)$^{(b)}$	k (10^{-6} FT/MIN) MAX. HYDR GRADIENT$^{(c)}$	L_L (%) P_L (%)	WOPT (%)$^{(d)}$ γ_D MAX. (P.C.F.)	G_S	ϕ' (°) c' (P.S.F.)	ϕ' (°) c' (P.S.F.)	COMPACTION METHOD$^{(h)}$	W γ_D (% OF PROCTOR)	
	A. MARINE AND ESTUARINE CLAYS (△)										
1	BERSIMIS No.2 1958	E C 8 5	— 5.0	29-46 18-23	24-30 98-88	2.72	— —	34.7 150	CONSTRUCTION EQUIPMENT	115 97	(1)
2	BEAUHARNOIS No.3 1958	R C 6 0	— 0.9	50 22	29 91	2.73	23.3 1000	31.2 250	CONSTRUCTION EQUIPMENT	107 98	—
	B. LACUSTRINE CLAYS (□)										
3	CARIBOU FALLS 1958	R S 3 5	0.005 1.0	79 25	29 89	—	— —	20.5 $^{(g)}$ 200	CONSTRUCTION EQUIPMENT	103 101	—
4	SEVEN SISTERS 1949	E C 2 5	— 0.2	19-114 11-38	17-27 113-94	—	— —	24 $^{(f)}$ 300	SHEEPSFOOT ROLLER	75-115 90-115	(1)
5	KELSEY 1959	R S 120	0.03 5.8	30-65 17-25	18-25 110-96	2.70	23 475	24.5 350	PNEUMATIC TIRED ROLLER	124 92	(10)
	C. GLACIAL TILLS – PLASTIC (●)										
6	NIAGARA STORAGE 1957	R S 6 8	0.05 2.8	41 21	20 104	2.70	— —	23-26 $^{(g)}$ 100	SHEEPSFOOT ROLLER	92 105	(1)
7	CONESTOGO 1957	E H 104	0.1 0.7	20-32 11-17	10-17 127-113	2.67	— —	— —	PNEUMATIC TIRED ROLLER	95-100 100	(1)
8	FANSHAWE 1952	E C 102	0.01 1.3	15-25 13-18	— —	2.65	— —	— —	CONSTRUCTION EQUIPMENT	95-100 100	(1)
9	ST MARY 1950	E H 200	— 0.8	35 14	15 113	2.71	28 425	— —	SHEEPSFOOT ROLLER	94 95	(1)
10	TRAVERS 1954	E C 145	— 0.6	32 15	16 112	—	— —	— —	SHEEPSFOOT ROLLER	93 97	(1)
	D. GLACIAL TILLS – NON-PLASTIC (○)										
11	MENIHEK 1953	E H 4 0	0.6 1.2	16 14	10 132	2.63 - 2.74	28 400	— —	SHEEPSFOOT ROLLER	80-120 95	(1), (2)
12	NICTAUX FALLS 1954	E C 9 0	— 0.6	— —	15 —	—	— —	— —	CONSTRUCTION EQUIPMENT	100 98	(1)
13	WEYMOUTH FALLS 1960	E H 104	— 0.5	— —	10 129	—	30 830	36.8 $^{(g)}$ 40	SHEEPSFOOT ROLLER	110 95	—
14	SISSON 1952	E H 8 5	5.0 0.4	— —	12-18 123-109	—	— —	— —	SHEEPSFOOT ROLLER	80-120 90-105	(1), (3), (4)
15	LAKE ST ANNE 1958	R S 120	30 4.5	NON-PLASTIC SILTY TILL	8 128	2.73	39 475	39 350	CONSTRUCTION EQUIPMENT	101 98	—
16	BERSIMIS No.1 1955	R S 225	4.0 6.0	NON-PLASTIC TILL	9 135	2.72	35.5 1370	38.0 1080	CONSTRUCTION EQUIPMENT	101 98	(1), (12)
17	CORNWALL 1958	E H 8 5	0.5 0.5	14 10	10 132	2.71	— —	39 $^{(g)}$ 0	SHEEPSFOOT ROLLER	96 101	(1)
18	SHAND 1942	E H 7 5	0.13 0.6	— —	9 134	2.74	32 970	— —	SHEEPSFOOT ROLLER	129 92	(1), (9) (11)
19	CANYON 1949	E C 192	— 0.8	— —	8 135	—	— —	— —	SHEEPSFOOT ROLLER	— —	(1), (5) (13)
20	KENNEY 1952	R S 317	— 8.1	— —	14 —	—	— —	— —	SHEEPSFOOT ROLLER	86-100 95	(1), (8)
21	ASH RIVER 1958	E C 8 0	— 3.0	25 15	10 135	2.91	34.5 1100	37.4 350	PNEUMATIC TIRED ROLLER	100 101	—
22	STRATHCONA 1957	E S 175	0.16 3.0	18 11	8 141	2.81	33 1250	40.0 200	PNEUMATIC TIRED ROLLER	100 100	(1)
23	SNARE RIVER 1948	E C 7 0	0.04 1.0	27 18	16 112	—	— —	— —	SHEEPSFOOT ROLLER	— —	(1), (6)
	E. RESIDUAL SOILS AND SOFT BEDROCK (▽)										
24	CHIN 1955	E H 7 2	— 0.4	28-34 16-17	14-19 112-105	—	— —	— —	SHEEPSFOOT ROLLER	90 95	(1)
25	BOUNDARY 1957	E H 9 5	— 0.6	31 19	17 111	—	32 575	— —	SHEEPSFOOT ROLLER	100 96	(1)

NOTES

(a) EH – EARTHFILL, HOMOGENEOUS SECTION
EC – EARTHFILL, CENTRAL CORE
ES – EARTHFILL, SLOPING CORE
RC – ROCKFILL, CENTRAL CORE
RS – ROCKFILL, SLOPING CORE

(b) MEASURED ABOVE ORIGINAL RIVER BED LEVEL.

(c) RATIO OF SHORTEST SEEPAGE PATH TO HEAD IN SECTION WITH MAXIMUM HEIGHT.

(d) MEASURED IN STANDARD PROCTOR TEST.

(e) SEE REFERENCES AND ACKNOWLEDGEMENTS AT END OF PAPER

(f) SHEAR STRENGTH PARAMETERS USED IN DESIGN.

(g) WATER CONTENT DURING TEST PROBABLY GREATER THAN 125% OF OPTIMUM.

(h) WHERE "CONSTRUCTION EQUIPMENT" IS INDICATED COMPACTION WAS OBTAINED BY USE OF HAULING AND SPREADING EQUIPMENT ONLY.

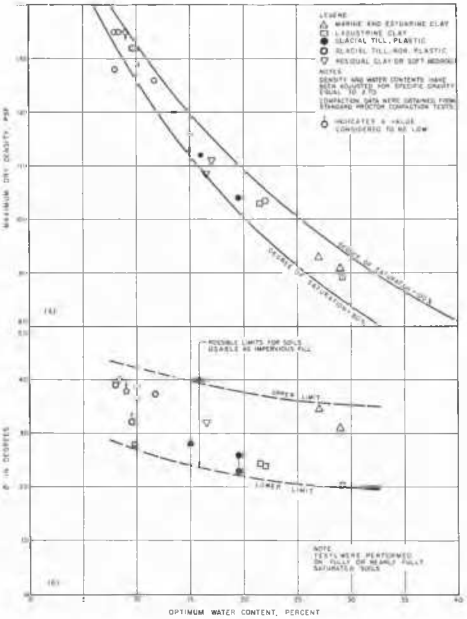

Fig. 4 W_{opt} vs. γ^{d}_{max} and Φ' for Impervious Fill Materials in Canadian Dams.

W_{opt} en fonction de γ^{d}_{max} et Φ' pour les matériaux de remblais imperméables dans les barrages canadiens.

contents between 24 per cent and 30 per cent. For both clays Φ' is between 30 degrees and 35 degrees.

Three lacustrine clays, all deposits of Lake Agassiz, have been used in dam construction and are included in Group B of Table 1. The plasticity of these clays is variable because of their varved structure and differential weathering, but in general the clays are of moderate to high plasticity. They have clay fractions ranging from 30 per cent to 50 per cent, very low permeability, and optimum water contents between about 20 per cent and 30 per cent. Their shear strengths are much lower than those of the Group A clays, Φ' being characteristically between 20 degrees and 25 degrees.

The eighteen glacial tills listed in Table 1 can be divided on the basis of grain size into two groups (see Fig. 3 (C) and (D)). Five of these tills, Group C, three from Southwestern Ontario and two from Southern Alberta, are typical of the thick clay till sheets which are underlain by sedimentary rocks. These plastic tills have clay fractions ranging from 15 per cent to 30 per cent, moderate plasticity, and low permeability. Their optimum water contents vary from 10 per cent to 20 per cent, while from the few data available Φ' might be expected to be between about 23 degrees and 30 degrees. The Group D tills have clay fractions which attain a maximum of about 15 per cent, and because of the small amount of clay they exibit little or no plasticity. The permeabilities of these tills can be expected to vary rather widely between limits such as the silty Lake St. Anne till ($k = 30 \times 10^{-6}$ ft/min) and the more clayey Strathcona till ($k = 0{\cdot}16 \times 10^{-6}$ ft./min). Optimum water contents characteristically range from about 8 per cent to 15 per cent. The well-graded granular nature of these tills and their low clay contents combine to produce Φ' values which range between 35 degrees and 40 degrees.

Since the compositions of residual soils can vary widely depending on the parent rock and weathering processes, no generalizations of their properties can be made. The cases of Chin Dam and Boundary Dam are included here solely to illustrate the use of these types of soil.

Significance of Impervious Fill Types in Dam Construction :

It is interesting to note that in eighteen of the twenty-five dams listed in Table 1 glacial tills were used for the impervious fill. The common occurrence of tills has undoubtedly been a major factor in its more frequent use, but it is also probable that where a till and a clay are equally favoured by economy and availability, the till would more likely be chosen for its greater strength and possibly better placing properties. Nevertheless, it is interesting to note that the more plastic and usually weaker marine, estuarine, and lacustrine clays have been successfully used in areas where till is absent. The use of such clays is a comparatively recent development, and thus far they have only been used in core type structures of modest height. The Kelsey Dam, with a maximum height of 120 feet, is believed to be the highest structure in Canada to have a plastic clay core.

The geotechnical properties of glacial tills vary considerably, between, for instance, the moderately plastic Niagara till with a $k \simeq 5 \times 10^{-8}$ ft./min and a $\Phi' \simeq 23$ degrees to 26 degrees, and the non-plastic Lake St. Anne till for which $k \simeq 3 \times 10^{-5}$ ft./min and $\Phi' \simeq 39$ degrees. The tills included in Groups C and D have been successfully used in homogeneous dams and in central and sloping core dams. In the dams greater than 150 feet in height, tills have been used exclusively.

An examination of Table 1 reveals an interesting correlation between the type of till and the underlying rock. The plastic tills shown in Fig. 3 (*C*), which have clay fractions ranging from 15 per cent to 25 per cent, are found in the Plains Region, an area underlain by the softer sedimentary rocks, whereas the semi-plastic and non-plastic tills shown in Fig. 3 (D), having clay fractions below 15 per cent, are found in the three physiographic regions largely underlain by the harder igneous and metamorphic rocks. The deficiency in clay-sized particles is most evident in tills from the Canadian Shield as, for example, Bersimis No. 1 and Lake St. Anne.

Fig. 4 shows the value of γ^{d}_{max} and Φ' plotted against W_{opt}, with the values of γ^{d}_{max} adjusted to a common value of $G_s = 2{\cdot}70$. It can be seen that the plotted values constitute a narrow band within which the several soil type groups are rather distinctly separate. Of greater interest in the design of dams, however, is the relationship between W_{opt} and Φ'. All values lie in a band for which the possible upper limit varies from about 45 degrees to 35 degrees as W_{opt} increases, and the possible lower limit similarly varies from about 25 degrees to 20 degrees. The Φ' values for the non-plastic tills and the marine and estuarine clays lie near the upper limit, whereas the values for the pastic tills and the lacustrine clays, lie near the lower limit.

In Table 1 values have been presented, wherever possible, for the shear strength parameters, Φ' and c', at two water content conditions. The first sets were obtained at optimum water content conditions, and in most cases they show moderately high values of c'. It has been customary to use these values of Φ' and c' to determine the stability at the end of construction, but because of the existence of negative pore water pressures in samples tested at about optimum water content the apparent values of Φ' and c' obtained are respectively lower and higher than the true values. More realistic values of these two parameters can be obtained in tests performed with water contents higher than optimum, and for this reason the second sets of shear strength data are included in Table 1. These higher values of Φ' are plotted in Fig. 4 B) and it s considered that they should be used in stability analyses together with the lower values of c' and correct values of the pore pressure parameters.

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