Modern Canadian Dams

Barrages modernes canadiens

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SUMMARY

This paper reviews the climatic, topographic, and geological features of Canada, in so far as they influence the design and construction of Canadian dams, and describes a number of major projects currently under construction in Canada.

Lying mostly north of the 49th parallel and forming a land mass some 5000 km wide, Canada has a continental steppe type of climate characterized by extremes of temperature and a relatively short frost-free summer season. The predominant influence in the formation of the Canadian terrain is the long sequence of glacial action, which began with the Pleistocene epoch a million years ago and completed its last retreat as little as five thousand years ago. Consequently, vast areas of the land mass of Canada are covered by a mantle of glacially transported material of varying type and thickness.

The dominant geological feature of Canada is the Canadian Shield covering approximately half the country in the form of a large "V" surrounding Hudson Bay and extending south into the United States near Lake Superior. Bordering this to the west is the Plains area, which is generally underlain by sedimentary rocks, deeply eroded by glacial action, and covered with a thick mantle of drift and lacustrine deposits. To the west of the Plains area is the Cordillera region of the Pacific Coast where the rocks have thrust upward to form a series of young mountain ranges separated by deep linear valleys. These valleys were deeply eroded and backfilled with morainal, lacustrine and alluvial deposits as the ice retreated. The Appalachian region of eastern Canada is an older mountain region which glaciation and erosion has reduced to relatively low relief. The drainage pattern is well defined in broad valleys and the region lends itself to the construction of relatively low dams. The northern half of Canada is characterized by a varying depth of permafrost which is a serious impediment to dam construction. There has been little construction of dams on permafrost. The Kelsey Generating Station in the Canadian Shield is a notable exception.

Seven Canadian dams have been selected for discussion. The first three, Arrow, Mica, and Duncan Lake are located in the Cordillera region and are examples of earth dams constructed in typical Cordillera valleys. Each dam presented different problems in design and construction. The important problems and their solutions are discussed. The Portage Mountain Dam, on the border between the Cordillera and Plains regions, is located on the Peace River where it escapes eastward from the Rocky Mountain Trench. The dam is a zoned earthfill structure containing 45 million cu. m. of material and will create one of the great storage areas of the world. The South Saskatchewan Dam, in the Plains region, has a length of some 5 km and contains 57 million cu. m. of material. Of particular interest in this dam is the Bearpaw shale underlying the site, which is in a state of elastic rebound,

SOMMAIRE

Cette communication passe en revue les caractéristiques climatologiques, topographiques et géologiques du Canada, dans la mesure où elles affectent la conception et la construction des barrages canadiens. Elle décrit un certain nombre de projets importants actuellement en cours de construction au Canada.

Situé presque entièrement au nord du 49^{e} parallèle et formant une masse terrestre de quelques 5000 km de large, le Canada a un climat du genre steppe continentale, caractérisé par des extrêmes de température et une saison d'été sans gel relativement courte. La formation du sol canadien a été influencée de façon prédominante par la longue séquence d'action glaciaire qui commença au Pléistocène il y a un million d'années, et acheva son dernier recul il y a à peine cinq mille ans. Il s'ensuit que de vastes étendues de cette masse terrestre canadienne se trouvent recouvertes d'une couche de matériaux d'origine glaciaire, de types et d'épaisseurs variés.

Le caractère géologique dominant au Canada est le Bouclier canadien dont la forme en "V" couvre environ la moitié du pays, contournant la baie d'Hudson pour s'étendre au sud jusqu'aux Etats-Unis, près du lac Supérieur. Immédiatement à l'ouest se trouve la région des prairies, dont la sous-couche est en général constituée de roches sédimentaires profondément érodées par l'action glaciaire et recouvertes d'une couche épaisse de débris et de dépôts lacustres. A l'ouest de la région des prairies se situe les Cordillères de la côte du Pacifique. Là, les roches ont percé pour s'élever en une série de chaînes de montagnes jeunes séparées par de profondes vallées rectilignes. Le recul glaciaire éroda profondément ces vallées qui, par la suite, se comblèrent de dépôts morainiques, lacustres et alluviaux. A l'est du Canada, la région des Appalaches est une région montagneuse plus ancienne, dont le relief relativement peu élevé a été le résultat de l'action glaciaire et de l'érosion. Le tracé des cours d'eau est bien défini par de larges vallées, et la région se prête bien à la construction de barrages de hauteur relativement modérée. La moitié nord du Canada se caractérise par du pergélisol d'épaisseur variable, qui gêne sérieusement la construction de barrages. On n'a bâti que peu de barrages sur du pergélisol. Le projet Kelsey du Bouclier canadien est une exception notable.

Sept barrages canadiens ont été choisis pour cette discussion. Les trois premiers, ceux d'Arrow, Mica et Duncan Lake, sont situés dans les Cordillères et constituent des exemples de barrages en terre construits dans des vallées typiques de cette région. Chaque barrage posa des problèmes différents du point de vue de ses conception et construction. Les problèmes importants rencontrés, ainsi que leurs solutions sont discutés. Le barrage de Portage Mountain, sur la frontière entre la région des Cordillères et celle des prairies, est situé sur la rivière de la Paix à l'endroit où ce dernier débouche de la tranchée des Rocheuses. C'est un barpresenting difficult design and construction problems. The Manicouagan 5 Dam on the Canadian Shield is the one concrete structure included in the paper. It is a multiple-arch design and the largest structure of its type in the world. The Mactaquac Dam, in the Appalachian region, is a rock-filled structure with a central impervious till core.

In addition to these seven dams, seven additional modern dams are mentioned briefly.

rage en terre, à noyau imperméable, d'un volume de quarante-cinq millions de mètres cubes. Ce barrage créera un des plus grands réservoirs au monde. Le barrage de la South Saskatchewan, dans la région des prairies, mesure quelques cinq kilomètres de long et contient 57 millions de mètres cubes de matériaux. Les schistes de Bearpaw qui constituent la couche sous-jacente du noyau imperméable de ce barrage, étant dans un état de décompression élastique, sont d'un intérêt tout particulier, ayant causé des problèmes difficiles d'ordre technique et de construction de l'ouvrage. Le barrage Manicouagan 5 dans le Bouclier canadien est le seul exemple de barrage en béton compris dans cette communication. C'est un barrage à arches multiples et c'est la plus grande structure de ce type au monde. Le barrage Mactaquac, dans les Appalaches est un barrage en enrochement à noyau imperméable en argile à blocaux.

Outre les sept barrages mentionnés ci-dessus, sept autres barrages modernes sont décrits brièvement.

AT THE FIFTH INTERNATIONAL CONFERENCE IN PARIS (1961) a paper on earth- and rockfill dams in Canada entitled "The Geotechnical Properties of Impervious Fill Materials in some Canadian Dams" was presented by D. H. MacDonald, J. deRuiter, and T. C. Kenney. The present paper is in many respects a continuation of the work of these authors, since it too will deal primarily with earth- and rockfills, these having become the most popular structures in this country for the impounding of water—no doubt because of their adaptability to the Canadian climate, of the materials and foundations of our glaciated terrain, and of the facility of construction afforded by the introduction of heavy earthmoving equipment during the last thirty or forty years. Our work has been further facilitated by the Canadian *Register of Dams* which was published in June, 1965, by the Canadian National Committee on Large Dams and which contains an extensive reference bibliography in addition to a catalogue of structures. Reference has also been made to the Canadian General Paper presented by D. R. Nancarrow (1964) to the Eighth Congress on Large Dams in Edinburgh on behalf of the Canadian National Committee on Large Dams.

In preparing the present story on modern Canadian dams it was recognized that many of those attending this Conference may be visiting Canada for the first time. Accordingly, our remarks are prefaced by a brief description of the pertinent physical characteristics of our country. Later, when dealing with the dams separately brief reference will be made to the geology of each site to show how special problems have arisen and how they have been dealt with. Fortunately, the task has been made easier by the lectures in preceding technical sessions dealing with various aspects of the geology of North America.

GEOLOGY

The predominant influence in the formation of the Canadian terrain, and one which affects the design of many Canadian dams, is the long sequence of glacial action which began with the Pleistocene epoch a million years ago and completed its last retreat as little as five thousand years ago. Indeed, the recency of the Ice Age is one of the more fascinating aspects of Canadian topography. Those travelling across the country by air will no doubt be intrigued to observe the residues and erosions, and attempt a reconstruction of the concluding glacial action. For the Canadian dam designer, such preoccupation with the reconstruction of glacial movements and deposits becomes a necessity.

Fig. 1 is a map of Canada showing the simplified geological divisions of the country. The numbers within the circles show the locations of the modern Canadian dams to be discussed. The dominant feature is the Canadian Shield which covers approximately half of the country in the form of a large "V" surrounding Hudson Bay and extending into the United States to the south near Lake Superior. It consists of hard, erosion-resistant rocks of both volcanic and sedimentary origin formed during the Precambrian era. These rocks were scoured by glacial action of the Pleistocene epoch and left as a vast hummocky surface with ill-defined drainage patterns. The Shield's innumerable lakes have an aggregate area probably exceeding the lake area of the rest of the world put together.

The plains bordering the Canadian Shield are generally underlain by sedimentary rocks with a more or less horizontal stratification overlaying the Precambrian. These soft sedimentary rocks were deeply eroded by glacial action and left covered with a thick mantle or drift and lacustrine deposits. The largest of these areas is the interior plain extending from the Arctic Coast south into the United States. In southern Canada it rises from east to west, beginning at the edge of the Canadian Shield near Lake Winnipeg and terminating abruptly at the great Cordillera region of the Pacific Coast. The rocks of the Cordillera have been thrust upward to form a series of mountain ranges and plateau lands separated by deep linear valleys or trenches running generally in a northwest–southeast direction. These trenches were eroded to great depth prior to the last glacial period and backfilled with morainal, lacustrine, and alluvial deposits as the ice retreated. Up to 365 m of such unconsolidated material has been proven by drilling. As a general rule, however, the depth of material overlying the bedrock in these trenches is unknown. In some cases the rivers of the Cordillera have cut through from one trench to another in their descent to the ocean and have thereby created dam sites with relatively shallow depth of overburden at the intervening ridges. In other cases there is no alternative but to construct dams on the unconsolidated material of the valley floors.

The Appalachian region, like the Cordillera, is a mountain-building region of severe folding and faulting, but one of much greater age. Long periods of erosion combined with glaciation have reduced the region to one of relatively low relief, the highest mountain being located in the Gaspé Peninsula and having an elevation of 1270 m. The drainage pattern is well defined in broad valleys, and the region lends itself to the construction of relatively low dams utilizing concrete, rock, or earth construction.

CLIMATE

As may be surmised from the preceding review of geology, Canada has only recently emerged from the last Ice Age.

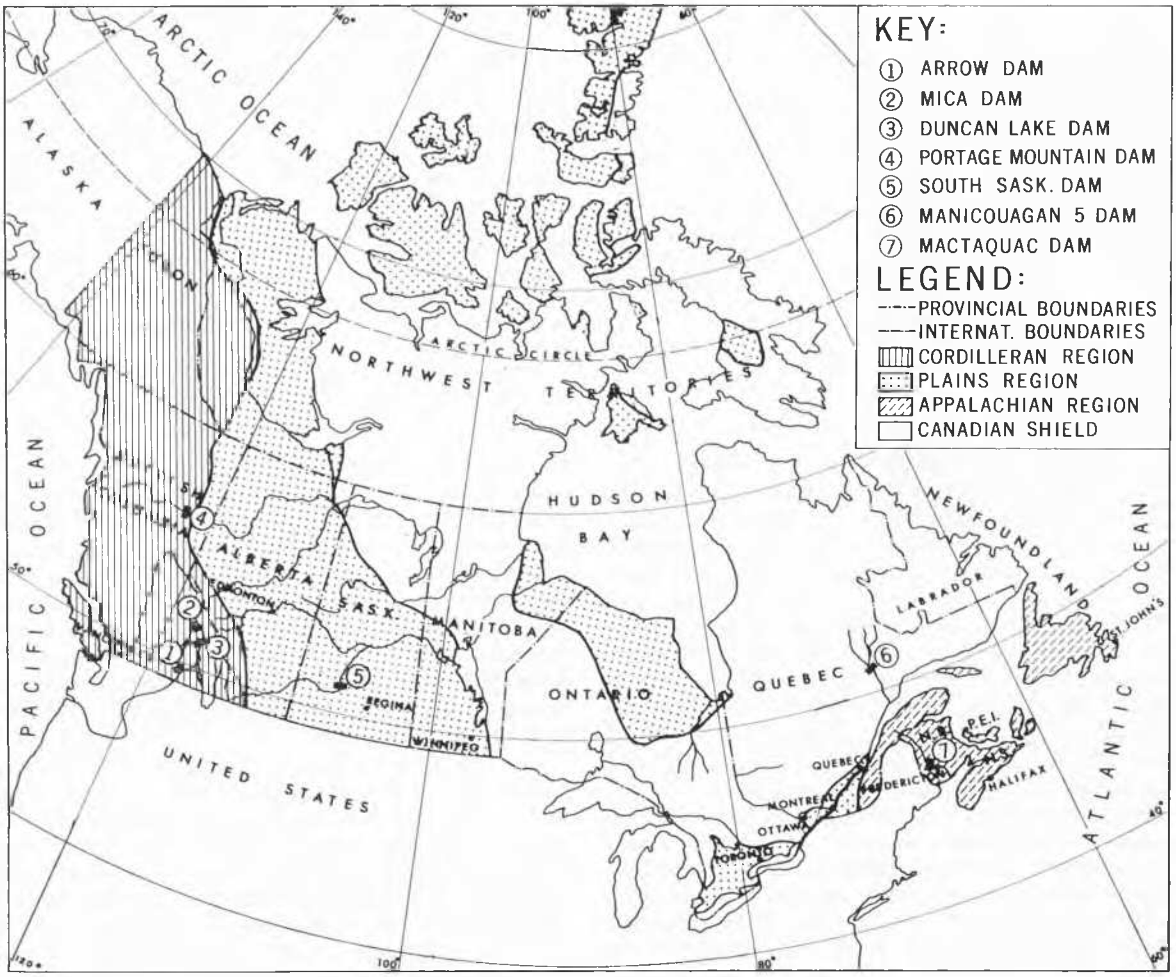

FIG. 1. Geological subdivisions.

Hence it is not surprising that arctic and subarctic climates prevail over a large part of the country. To the west the Rocky Mountains effectively limit the tempering influence of the Pacific Ocean to a relatively narrow coastal strip. On the east the effect of the Atlantic Ocean is minimized by cold currents sweeping down from the Arctic while the benign Gulf Stream escapes eastward to warm the shores of Europe. Thus Canada is left with a continental steppe type of climate with temperatures ranging seasonally between high and low extremes as the warm air masses from the south or the cold air masses from the Arctic regions predominate. The resulting winter season adds to the difficulty of constructing dams: costs increase during freezing weather; earthwork construction tends to be discontinuous; and much care must be given to concrete and masonry components to produce structures that will be resistant to repeated freezing and thawing cycles.

Fig. 2 is a map of Canada showing the isotherms of average annual temperature. In conjunction with Fig. 1 it serves to explain why the population and the economic development of this country tend to concentrate in the areas along the southern boundary (Fig. 3). These, of course, are the areas in which most of the dam construction in Canada is found.

PERMAFROST

One serious impediment to the northern expansion of economic development and dam construction in Canada is the permafrost, or permanently frozen ground which underlies the northern 40 to 50 per cent of the country as a legacy from the last Ice Age (Legget and Hardy, 1961). Permafrost is defined exclusively on the basis of temperature; hence it may exist in bedrock, gravel, sand, silt, peat, or mixtures of these materials. The surface or active layer is subject to annual freezing and thawing—usually to a depth of less than a meter—and may support extensive vegetation. The temperature of the underlying permanently frozen ground is also subject to seasonal variation to a depth of some 6 m, where it stabilizes at a value near the mean annual air temperature of the locality, and then rises with increasing depth at the rate of approximately 1 C per 80 m until the bottom of the permafrost is reached.

Depths of 350 m or more may be attained in the extreme north. These decrease progressively toward the south until permafrost areas become discontinuous, and eventually sporadic. The approximate southern limit of discontinuous permafrost is shown on Fig. 4. The northern limit of the tree line is shown for comparison.

Construction of dams or other major structures on permafrost in rock or free-draining, granular materials does not differ materially from such construction in more southern climates. The difficulty arises in the case of permafrost in fine-grained soils with high moisture contents. With non-hydraulic structures this problem is overcome by construction to preserve the underlying material in its permanently

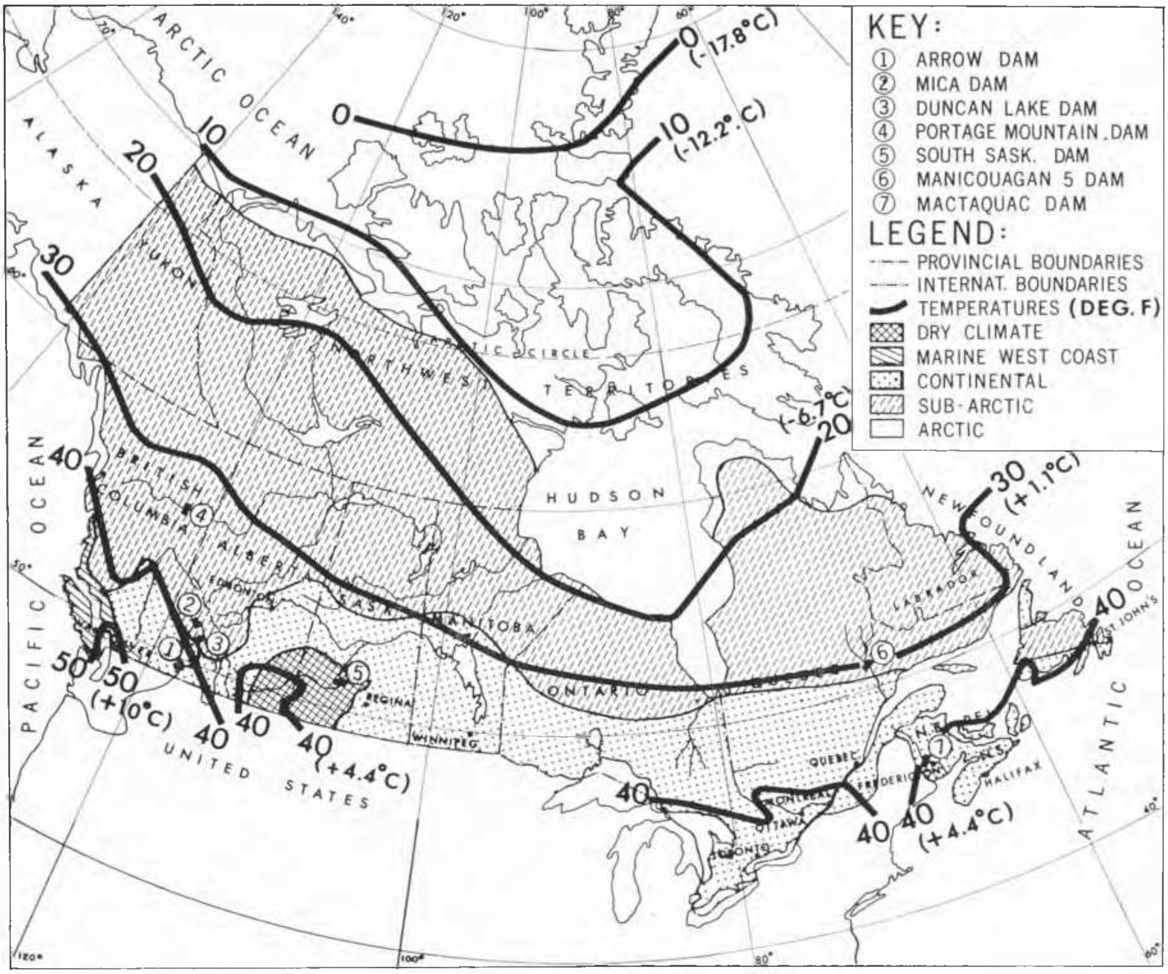

FIG. 2. Average annual temperatures and climatic zones.

frozen state. This, however, is not possible in the case of a dam impounding water. Hence, to date there has been little construction of dams on permafrost in Canada. One of the principal exceptions, at the Kelsey Generating Station on the Canadian Shield area of northern Manitoba, is described in the paper by MacDonald, Pillman, and Hopper (1960).

MODERN CANADIAN DAMS

The following seven Canadian dams have been selected for discussion in this paper.

No.	Name	River
1	Arrow	Columbia
2	Mica	Columbia
3	Duncan Lake	Duncan (Columbia)
4	Portage Mountain	Peace
5	South Saskatchewan	South Saskatchewan
6	Manicouagan 5	Manicouagan
7	Mactaquac	St. John

The locations have been shown on Figs. 1 through 4. Three are in the Cordillera, one on the boundary between the Cordillera and the Interior Plain, one on the Interior Plain, one on the Canadian Shield, and one in the Appalachian region. All are south of the permafrost zone. With the exception of No. 6 (Manicouagan 5), all dams are earth- or rockfills with concrete auxiliary structures. In a number of cases they are supplemented with tunnels for temporary or permanent diversion of water. This preference for earth- and rockfill structures in Canada follows the trend already illustrated by the Canadian *Register of Dams* which reports that of the 101 dams undertaken in Canada during the period 1954 through 1963, 55 per cent were of earth or rockfill, 31 per cent were of concrete gravity section, 2 per cent were concrete arch dams, and 12 per cent were of mixed design.

Arrow Dam

The Arrow Dam is No. 1 on Figs. 1 through 4. It and the Mica and Duncan Lake dams are the three Columbia River storage structures now being built in Canada as a result of the Columbia River Treaty with the United States. It is an earthfill dam about 50 m high located on the outlet of the Lower Arrow Lake at an elevation of approximately 425 m above sea level. It will contain approximately 8 million cu.m. of material, and is of particular interest since it will be constructed in the wet (i.e., without dewatering) over a pervious foundation of unknown depth.

The Columbia River Valley at the Arrow Lakes affords an excellent example of a valley of the Cordillera eroded to great depth during, or prior to the last Ice Age, and subse-

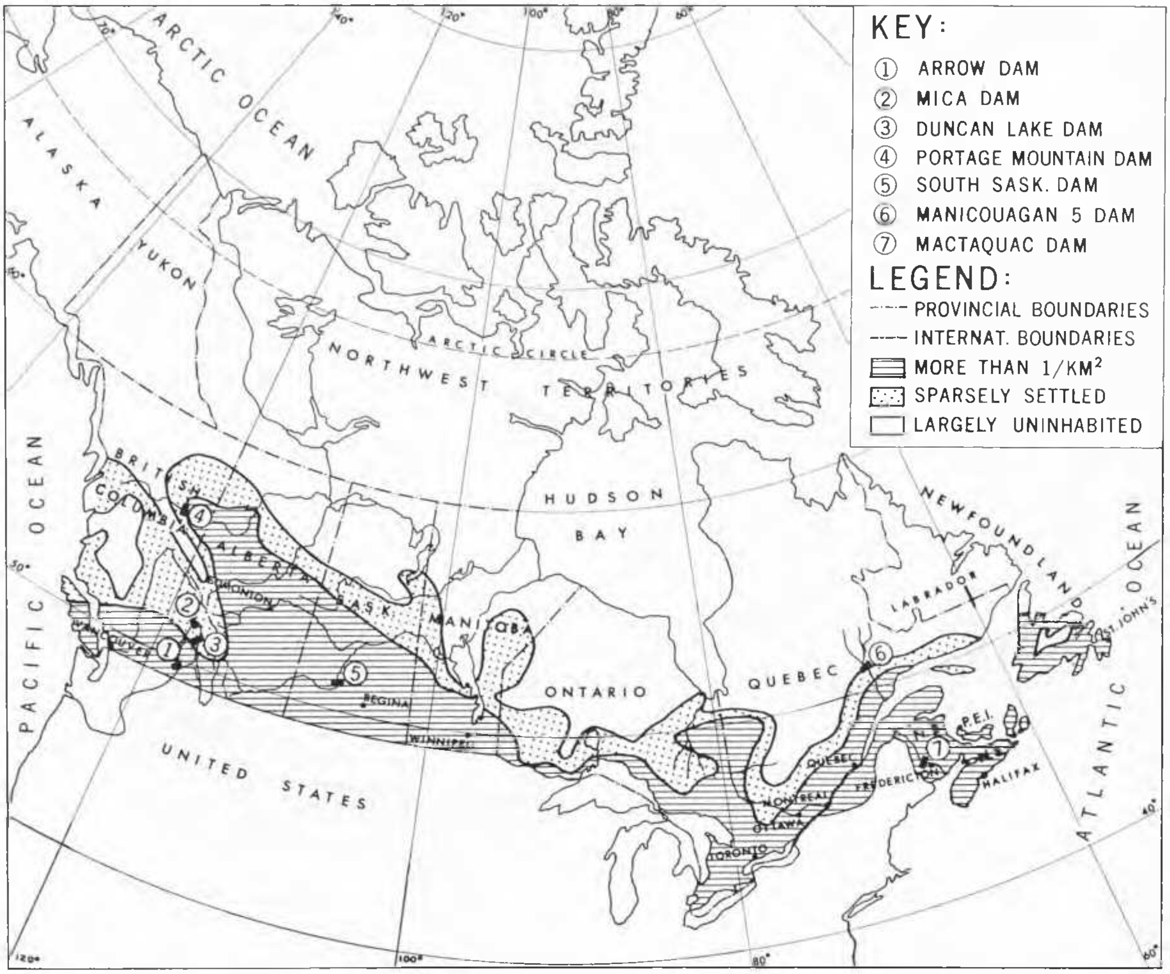

FIG. 3. Population density.

quently backfilled with fluvioglacial material. In this case the presence of a layer of volcanic ash of known age in the recent surface silt deposits indicates that the backfilling process was essentially completed at least 7000 years ago. Test drilling has been carried out to a depth of some 150 m without encountering bedrock and has indicated the materials of the river bed to consist largely of sands and gravels having a permeability of between 10^{-1} cm/sec and 10^{-2} cm/sec with random inclusions of open gravels. Fortunately, a sound rock spur on the left bank provides an excellent foundation for the concrete control structure, but will require an immense cofferdamming effort for dewatering. The cofferdam is being constructed of dumped sand and gravel. It is to be sealed by a cast-*in-situ* concrete diaphragm (cutoff wall) keyed into bedrock.

It is not practicable to dewater the river channel for the main dam. Hence the lower portion of this structure will be built in the wet. An embankment will first be built across the river by dumping sand and gravel into the water to divert the flow through the control structure. An inclined impervious core of glacial till will then be spread over the upstream slope by progressive displacement of material from the crest. The embankment will be completed to crest level by conventional rolled fill methods. A cross-section of the finished structure is shown on Fig. 5. The sloping core of till will be joined to an impervious blanket extending over the prepared bed of the river a sufficient distance upstream of the dam to produce a hydraulic gradient of 3 per cent under the blanket to the downstream toe of the dam. The thickness of the blanket will vary from 3 m at the upstream edge to approximately 5 m at the junction with the sloping core and, where placed in the wet, will never be less than one-quarter of the drop in head across the blanket. Prior to the placing of the blanket the bed of the river will be levelled with barge-dumped sand and gravel. The blanket itself will be similarly placed, using barges as large as practicable to avoid segregation. The entire operation of underwater construction without the use of filter layers is facilitated by the fact that till, sand, and gravel of favourable grading characteristics are found nearby.

A line of relief wells at 60-m centers will be located on the downstream slope of the dam. These wells are to extend some 30 m into the underlying sands and gravels of the foundation. The probable leakage has been calculated at 8500 liters/sec at most.

Construction of the dam was started in 1965. First filling of the reservoir is scheduled for 1969.

Mica Dam

This dam is No. 2 on Figs. 1 through 4. It is one of the three Columbia River Treaty storage structures and will also be used eventually as a power dam. It is located at an elevation of 565 m above sea level on the Columbia River where the latter cuts its way through the west wall of the Rocky

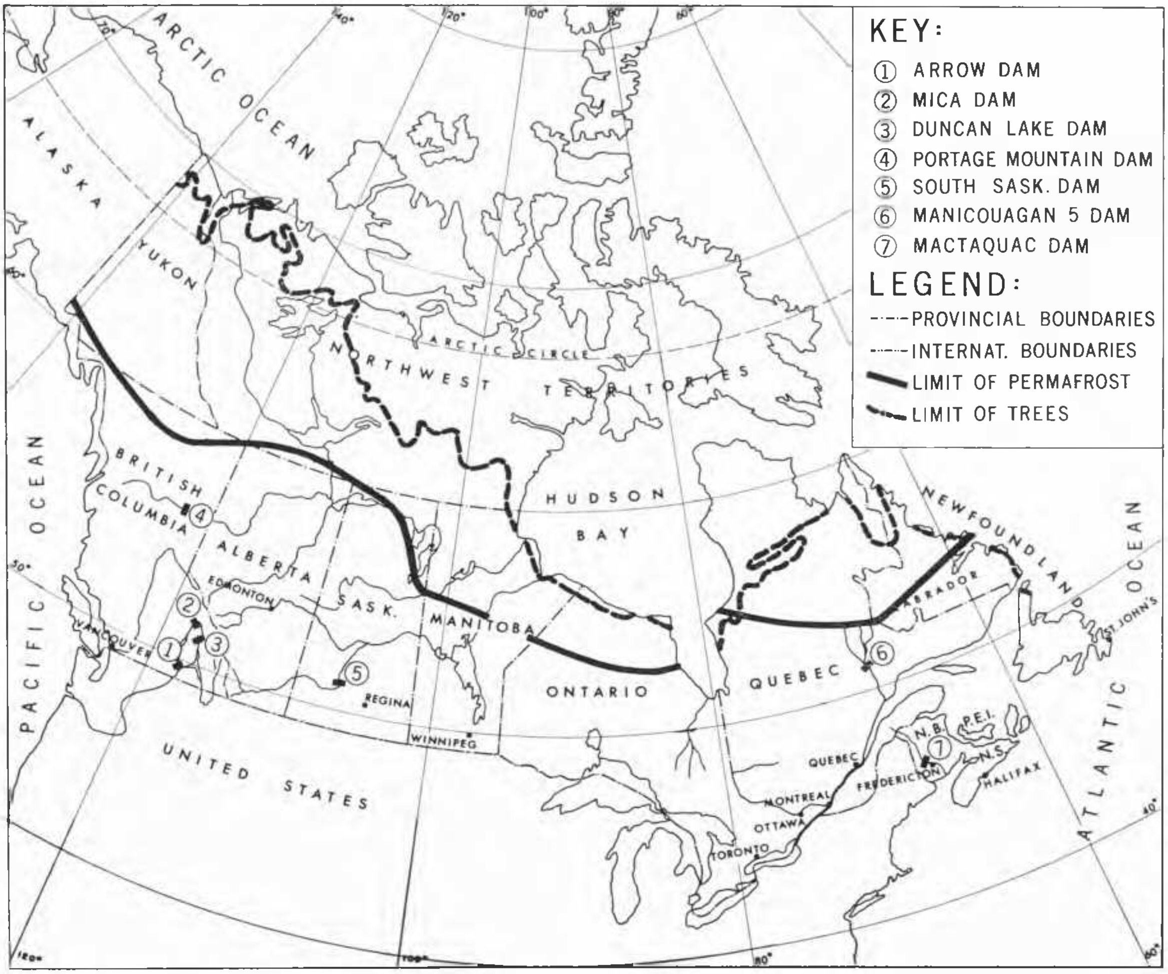

FIG. 4. Permafrost zone and tree line.

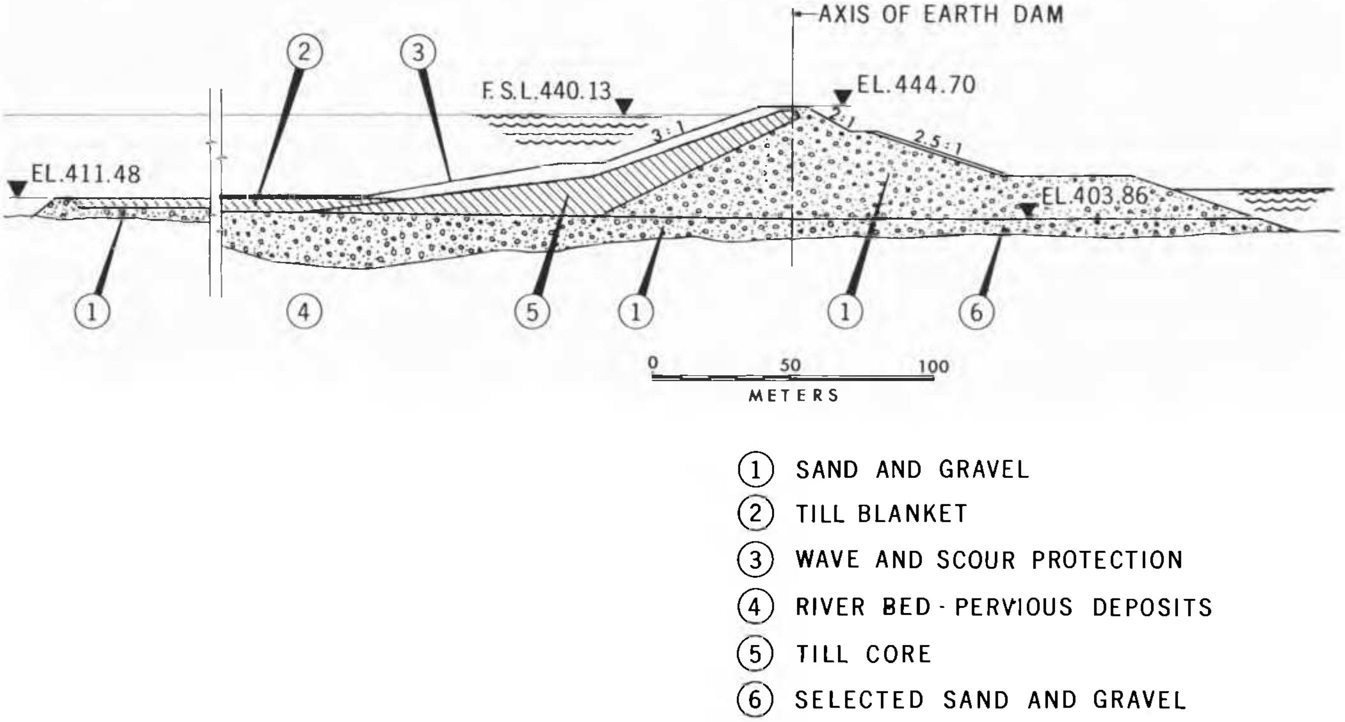

FIG. 5. Arrow Dam.

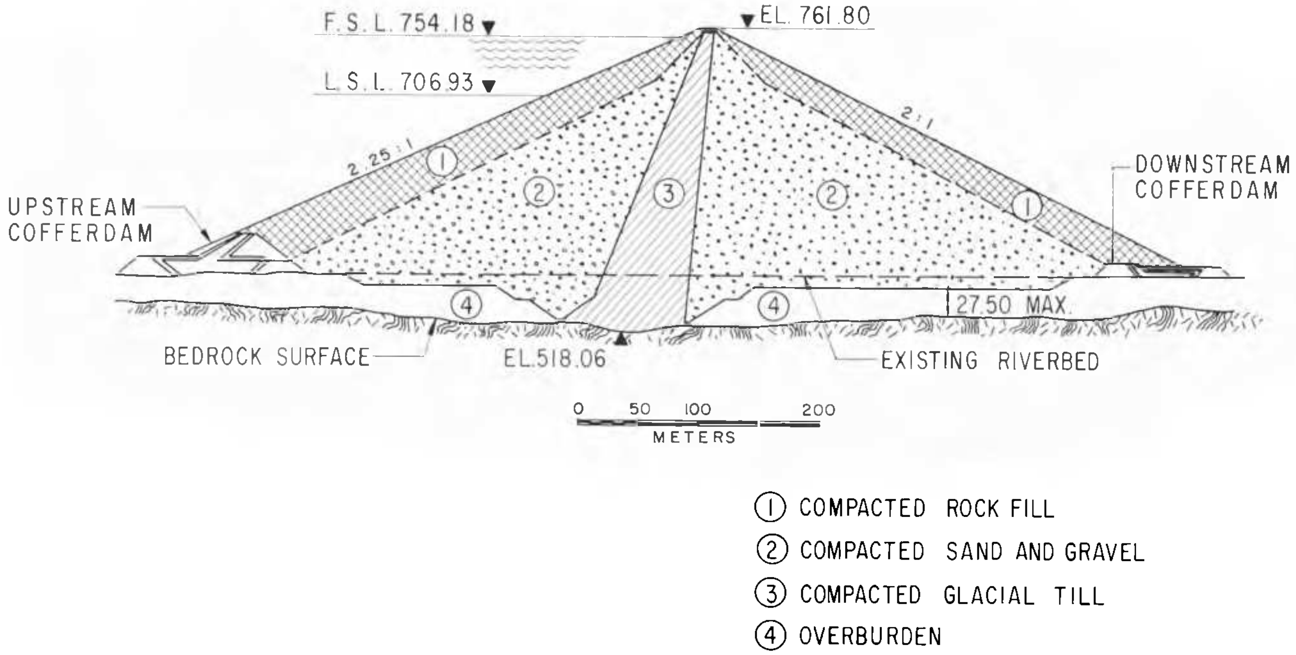

FIG. 6. Mica Dam.

Mountain Trench before turning south to flow toward the Canadian border. Hence, the foundation conditions are relatively simple, although still presenting significant problems. The rock at the site consists of a Precambrian series of mica schists and gneisses interbedded with granite. It has been eroded to form a V-shaped channel, and later backfilled with some 45 m of fluvial sands and gravels. Probably the most disconcerting feature of these foundation materials is the presence of isolated lenses and layers of uniform fine sand within the top 18 m of the deposits.

The dam will be an earth- and rockfill structure built in principle to the cross-section shown on Fig. 6. It will have a total height of some 240 m from the lowest point of foundation depth to the crest, and will contain 32 million cu.m. of material. The central core will be made from glacial till and founded in a trench excavated to bedrock. The adjacent transition zones, earthfill, and rockfill will be placed on the fluvial sands and gravels after removal of about 18 m of material from the riverbed to assure the elimination of most of the uniform fine sand. Biotite schists and fine-grained gneisses and granites will be used in the rockfill portions and compacted dry with vibratory equipment. Depending on tests yet to be made, the maximum size may vary between 60 and 75 cm.

Construction is planned for a five-year period so that the entire project will be operational for storage purposes by April 1, 1973.

Duncan Lake Dam

This dam, No. 3 on Figs. 1 through 4, is located on the Duncan Lake tributary of the Columbia River system at an elevation of 545 m above sea level and is the third of the Columbia River Treaty storage dams. The completed structure will be approximately 40 m high and will contain 5,500,000 cu.m. of material. Its primary interest derives from the unusual foundation conditions encountered.

Like the Arrow Dam, the Duncan Lake structure is located in a valley that has been scoured to great depth and subsequently backfilled with fluvioglacial materials. The subsurface cross-section of the valley was investigated to its full depth by a combination of test drilling and seismic measurements, the drilling extending to a maximum depth of 185 m and checking the seismic profile to within 10 per cent. The resulting cross-section is shown on Fig. 7. The valley bottom is approximately 655 m wide and overlies an eroded channel indicated to be 380 m deep. The side walls of this buried channel converge uniformly to a width of 225 m at a depth of 200 m, and then appear to drop vertically to form a bottom canyon 180 m deep.

The unconsolidated material underlying the valley floor can be divided into three zones. The bottom zone consists of some 260 m of dense sands and gravels probably deposited as a moraine by early glacial action and consolidated under great pressure. This bottom zone has little or no effect on the design of the dam. The intermediate zone consists of about 110 m of varved lacustrine deposits of silt and fine sand, probably representing seasonal variations of deposition in the glacial lake that once filled the valley. The top zone consists of some 10 m of unsorted and highly pervious sands and gravels of fluvial origin.

The sands and gravels of the top zone have a permeability ranging from 0.4 cm/sec to 3.3 cm/sec. The fine sands and silts of the intermediate zone are relatively impervious in the vertical direction, but have a horizontal permeability varying from 1×10^{-2} cm/sec to 3×10^{-4} cm/sec. Most of the silt samples from the intermediate zone were found to be non-plastic, and such samples as indicated plasticity had a natural moisture content either close to or higher than the liquid limit.

In the design of the dam particular attention was paid to the problem of seepage through the top zone, and to the twin problems of settlement and stability in the intermediate zone. The resulting cross-section is shown on Fig. 8. It consists of a zoned earthfill with a thick, sloping core extending 150 m beyond the upstream toe of the dam as an impervious blanket. In addition there is a 3-m wide cutoff trench located under the upstream toe of the dam and penetrating well into the intermediate zone of the silts and sands. The function of

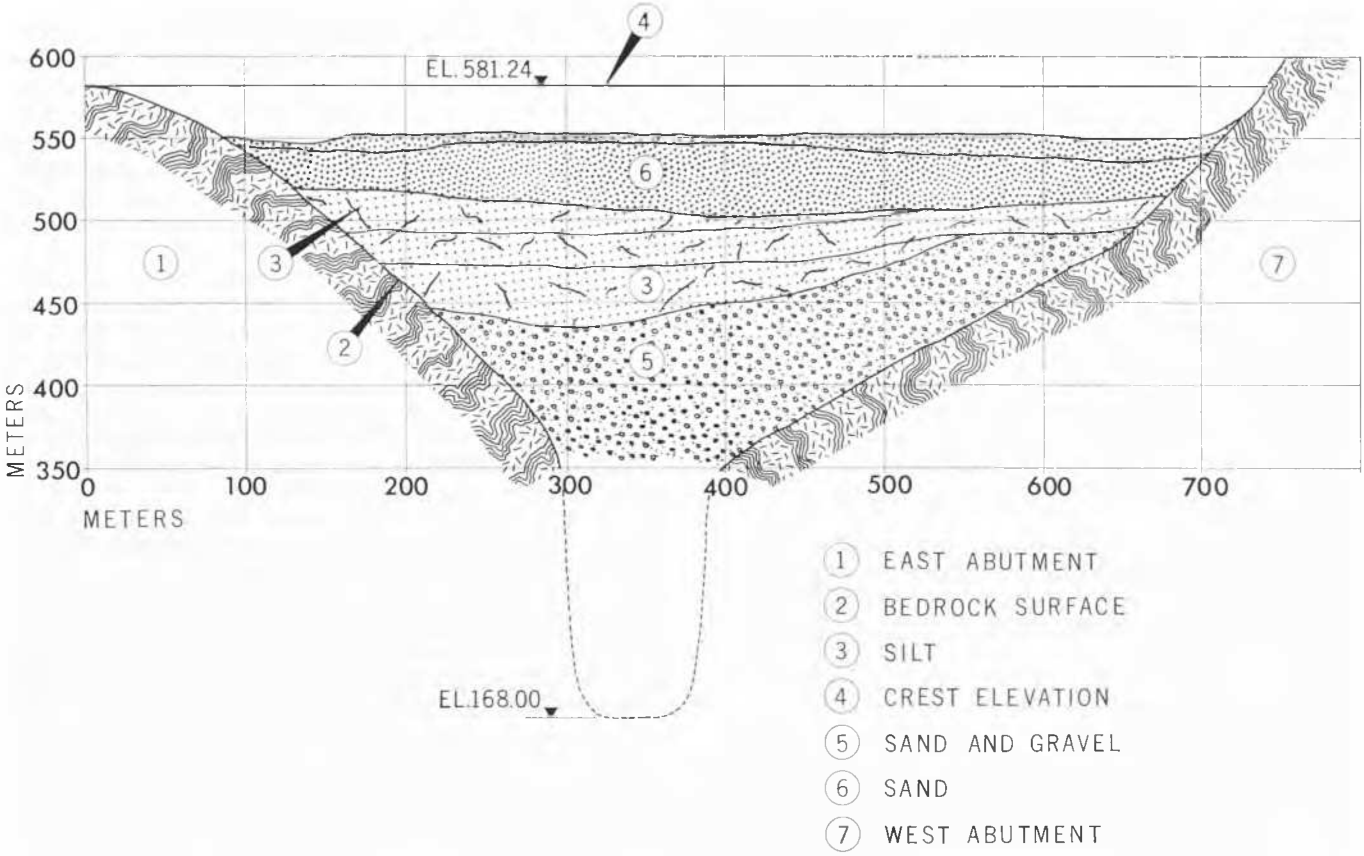

FIG. 7. Duncan Lake Dam site—foundation profile.

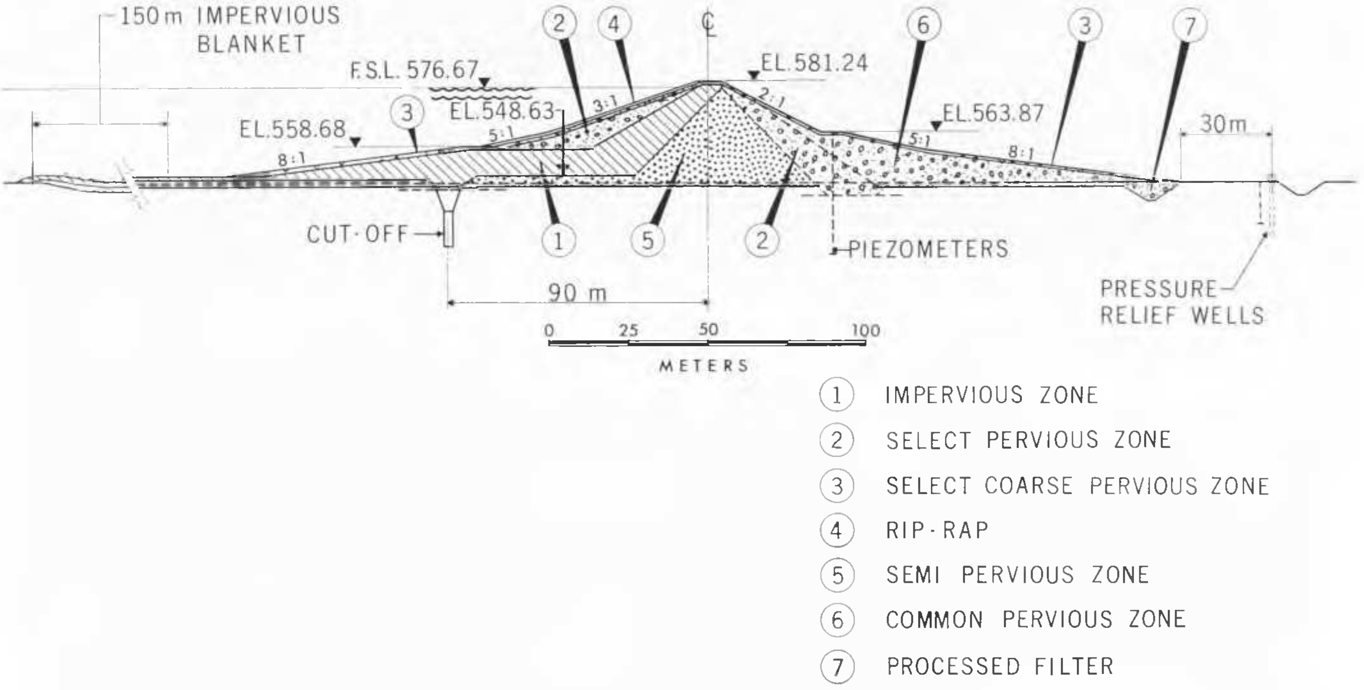

FIG. 8. Duncan Lake Dam—typical cross-section.

this cutoff is to intercept seepage through the top zone of pervious sands and gravels.

It has been excavated in the wet, using a bentonite slurry to prevent sloughing of the side walls, and backfilled with suitably graded glacial till to displace the slurry. The provision of both impervious upstream blanket and cutoff trench is somewhat unusual, and has been adopted in this case to provide two lines of defence against excessive seepage that might result from rupture due to settlement or unexpectedly porous channels through the top zone of the foundation. It is estimated that total settlement of this structure under load will be approximately 3 m.

Pressure relief wells will be located 30 m. downstream of the downstream toe. If the cutoff trench were ignored, the hydraulic gradient from the upstream edge of the impervious blanket to the relief wells would be 6 per cent.

In order to maintain an adequate factor of safety, the side slopes of the lower half of the dam vary between 5 to 1 and 8 to 1, while conventional side slopes prevail for the upper half.

Construction is now in progress and is scheduled for completion not later than 1968. If settlement and dissipation of pore pressure proceed at a satisfactory rate, construction may be accelerated to reduce the scheduled time by one year.

Portage Mountain Dam

Portage Mountain Dam, No. 4 on Figs. 1 through 4, is located on the Peace River where the latter escapes eastward from the Rocky Mountain Trench by cutting through the Rocky Mountain Range at an elevation of some 500 m above sea level. The dam site results from glacial action about 10,000 years ago when immense quantities of morainal material were deposited in the valley of the Peace which then flowed in a deep channel on the north side of the Portage Mountain. The river was thus diverted to the south side of the mountain where it cut its present channel and created the dam site with foundation rock at shallow depth in the river. A hole, 520 m. deep, was drilled into the moraine over the original channel to an elevation of 150 above sea level without encountering bedrock.

As shown on Fig. 9, the dam is being built as a zoned earthfill structure 180 m high. It will contain some 45 million cu.m. of material and will create one of the great storage reservoirs of the world with a utilizable volume of approximately 40 billion cu.m. The underground power plant associated with the project will have a total capacity of 2,300,000 kilowatts in ten units. The first unit will be operational in 1968. The other units are planned for installation in stages terminating in 1975.

The unique feature of the Portage Mountain Dam, apart from its size, is the method adopted for its construction. All the 45 million cu.m. of material entering into the structure will consist of silts, sands, and gravels obtained from the moraine north of Portage Mountain. They will be transported to the site by what is probably the world's largest conveyor system, having a length of 4.6 km and a capacity of about 5100 cu.m., or 11,000 metric tons, per hour.

On arrival at the site approximately half the material will be placed directly in the upstream and downstream embankment zones. The remaining half will be screened, washed, and blended for the impermeable core, the filters, and the

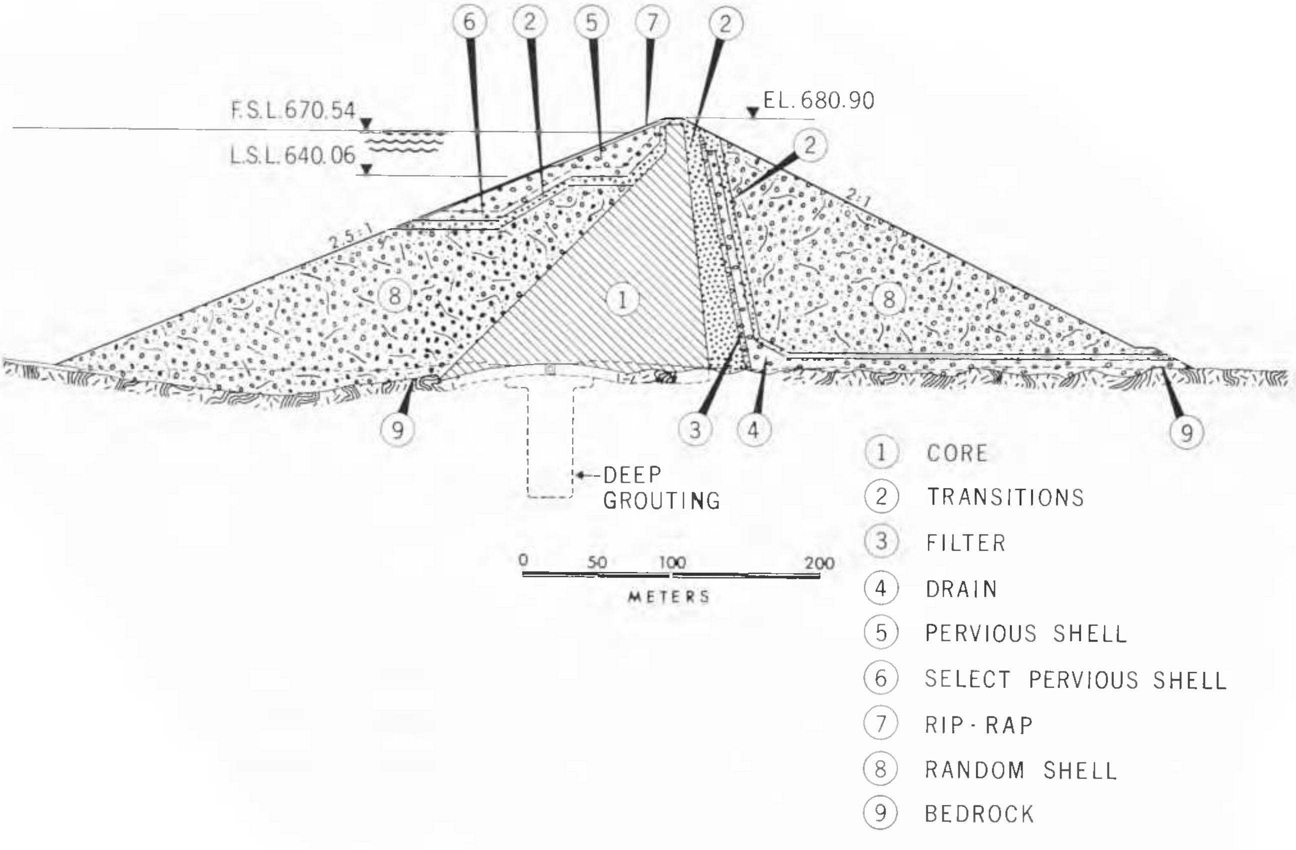

FIG. 9. Portage Mountain Dam.

transition zones. In addition to the 45 million cu.m. required for the dam an appreciable volume of fine material will have to be wasted in the washing process to obtain filter materials.

The construction of impervious core from processed silts and sands on such a large scale is also an unusual feature. About 9 million cu.m. of material conforming to the following mechanical analysis will be required:

Sieve	Per cent passing
¾ in.	100
No. 4	75 to 100
No. 20	50 to 80
No. 60	35 to 60
No. 200	25 to 35

The original investigations disclosed a deposit of clay which might have been used in its natural state for the impervious core, but the processed silty-sand core was adopted as being both more practical and more conservative.

Owing to the presence of pervious strata, an extensive grout curtain has been provided under the dam to control foundation uplift and seepage volume. The rock has been consolidated by area grouting to a depth of 7 m over the full base width of the impervious core, and a five-line grout curtain has been added to a depth of from 60 to 100 m. This programme was preceded by large-scale experiments to determine the optimum design of the curtain (Benko, 1964). A drainage system comprising approximately 3.5 km. of tunnels has been added on the downstream side of the grouted cutoff.

South Saskatchewan Dam

This dam is No. 5 on Figs. 1 through 4. It is an earthfill structure of impressive dimensions, almost completely filling the South Saskatchewan valley at a point where suitable cross-section and an abundance of sands, gravels, alluvial clays, and glacial tills facilitate construction. The valley is approximately 67 m deep, and the height of the dam is 64 m. The dam has a length of some 5 km, contains 57 million cu.m. of material, and involves an excavation of 82 million cu.m. in volume. The cross-section of the valley at the site is shown on Fig. 10, from which it will be noted that that erosion has scoured a V-shaped channel some 60 m into the shale. A depth of 15 to 30 m of glacial drift is perched at the top of the two side slopes. Subsequently the valley was backfilled with about 33 m of alluvial sand on which the river now flows at an elevation of 500 m above sea level. The dam has been founded on this sand. It has a horizontal permeability varying from 5×10^{-2} to 7.5×10^{-2} cm/sec and a vertical permeability of approximately 7×10^{-3} cm/sec.

The cross-section of the dam is shown on Fig. 11. It will be noted that the slopes of both upstream and downstream

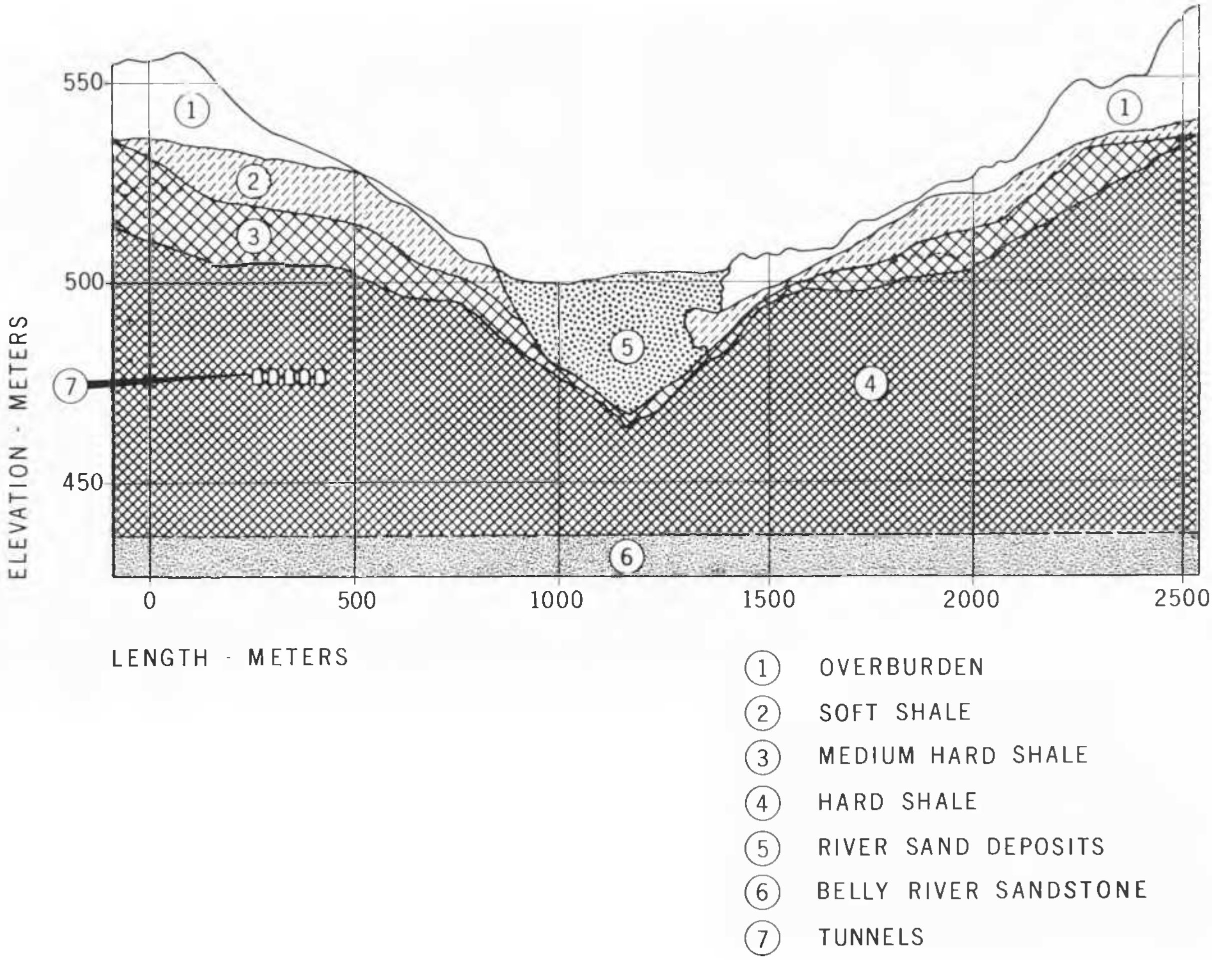

FIG. 10. South Saskatchewan Dam site—foundation profile.

embankments vary from 12 to 1 for the bottom half of the structure to 2 to 1 near the crest. An impervious blanket extends 760 m upstream of the axis of the dam, and pressure relief wells of the United States Army Corps of Engineers type are located on 23 m centers along the downstream toe. The length of seepage path from the upstream edge of the impervious blanket to the pressure relief wells is 1160 m and corresponds to a hydraulic gradient of 5 per cent.

The Bearpaw shale underlying the site has created difficult problems (Ringheim, 1964). This shale is derived from marine deposits of the Upper Cretaceous age which were buried under some 750 m of superimposed sediments before glacial action scored off the upper sedimentary levels and left the shales in their present position near the surface. These shales are now in a state of elastic rebound and they continue to demonstrate their elastic properties. With excavation of surface material, the underlying shales have been found to rebound an amount equal to about 0.7 per cent of the depth of excavation. Conversely, they settle in somewhat similar proportion when loaded with dam embankment.

Since removal of loading by glacial action these shales have also undergone a non-elastic increase in volume accompanied by a loss of cohesive strength due to absorption of water. The swelling, and hence the water content, is greatest at the surface and decreases with depth. This is a long-term action in which the shales at the site are now approaching equilibrium. For convenience in describing this condition, the engineers have considered the shale to be divided into the three zones shown on Fig. 10. The highest zone is the soft shale with a moisture content in excess of 29 per cent; the middle zone is the shale of medium hardness having a moisture content between 25 per cent and 31 per cent; the bottom zone of indefinite thickness is the hard shale having a moisture content of less than 27 per cent. The maximum moisture content encountered in the top zone was 35 per cent, and the minimum encountered in the bottom zone was 19 per cent. Corresponding variation in density was from 1,360 to 1,730 kg/cu.m.

This condition of the foundation shale has given rise to particularly difficult problems in the driving of tunnels, and in the design of abutment excavation and adjacent sections of the dam. The problem with respect to tunnel driving has been minimized at the expense of increased quantities by locating all tunnels in the bottom, or hard shale zone. Field tests have indicated a vertical pressure on the lining of such tunnels approximately equal to the overburden load, and a horizontal pressure about 50 per cent greater. Embankment and excavation slopes have been designed so as not to exceed the shear strength of the shale derived from analyses of actual side slopes of the valley.

Approximately 22 km upstream of the South Saskatchewan Dam, at a point where the river makes a sharp bend to the left, there is a depression in the east wall of the valley where the river course flowed through the Qu'Appelle Valley prior to the last glacial period and thus found its way to the Mississippi. In order to contain the new South Saskatchewan reservoir, it has accordingly been necessary to add a dam in the Qu'Appelle Valley to block this ancient channel. This dam is a zoned earthfill structure similar in cross-section to the South Saskatchewan Dam. It has a maximum height of 27 m, a length of 3.1 km, and contains approximately 11 million cu.m. of material. Hence the entire South Saskatchewan project comprises two dams of large dimensions, one to block the present river channel and the other to block the channel of recent glacial history.

Manicouagan 5

No. 6 on Fig. 1 through 4, this dam is located on the Manicouagan River on the Canadian Shield at an elevation of 210 m above sea level, where it will create one of the great storage reservoirs of the world having an area of over 2000 sq.km. and a utilizable volume of 144 billion cu.m. Construction is now sufficiently advanced to permit a start on filling of the reservoir. This is expected to take 7½ years. Associated with the project is a power station which will have an installed capacity of about 1⅓ milion kilowatts.

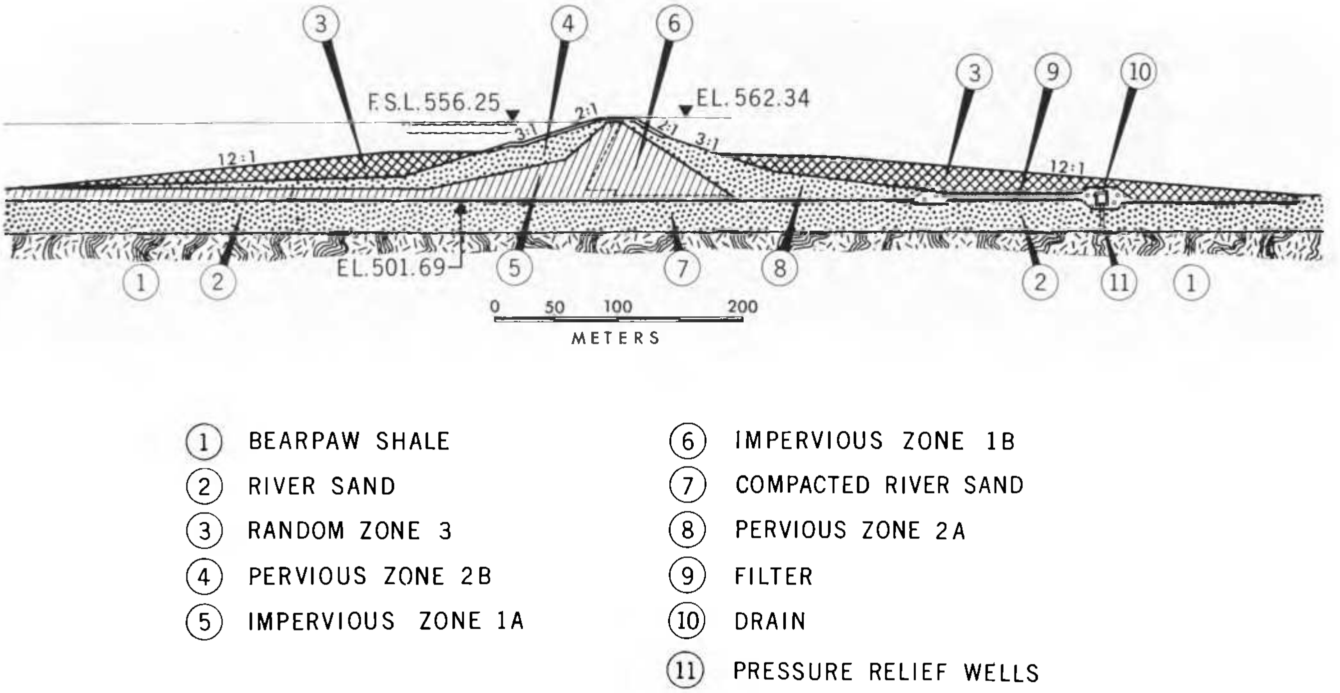

FIG. 11. South Saskatchewan Dam—typical cross-section.

Unlike the other dams discussed in this paper, Manicouagan 5 is a concrete structure (Fig. 12). It is of multiple-arch design with a central arch of 162 m span over the river channel and 13 arches of 76 m span on the two flanks—eight on the left and five on the right. The over-all length is 1,280 m, and the maximum height from foundation to crest is 216 m. It is the largest structure of its type in the world, and, as is to be expected, its design and construction have encountered a number of interesting problems—beginning with foundation preparation, which may be of interest to this meeting.

The Manicouagan River flows through a channel which was deeply eroded by ice action during the Pleistocene epoch. No geological faulting is involved. Ice action is clearly demonstrated by the fact that the bottom of the channel slopes upward in a downstream direction at the dam site. With the retreat of the glaciers the channel was backfilled with alluvial sand, gravel, and boulders without stratification or zoning. This material had an average permeability of 0.5 cm/sec and a maximum permeability of 1.0 cm/sec. It had a depth of 61 m at the upstream cofferdam, 46 m at the main arch of the dam, and 24 m at the downstream cofferdam—thus reflecting the upward slope of the bedrock.

Construction of the cofferdams and dewatering of the site of the main arch were complicated because topographical considerations dictated a location of the upstream cofferdam within 180 m of the foundation of the main arch—as may be seen on Fig. 13. In addition to restriction of space there was also a time limitation requiring dewatering of the site within eight months of the start of the operation. After close study of the situation by a special committee, it was decided to use simple earth dykes on top of the alluvium at both upstream and downstream cofferdam locations and to provide each with a special cutoff to rock.

At the upstream cofferdam the cutoff was made with a concrete membrane constructed to a maximum depth of 70 m by the Icos-Veder process in which the concrete is placed in a series of drilled holes temporarily stabilized by a bentonite slurry. The method bears some similarity to that used at Duncan Lake for the impervious till cutoff in that both methods make use of bentonite slurry to stabilize the walls of deep excavations, although method and materials of backfill are entirely different.

For the downstream cofferdam the Solétanche-Rodio method of grout injection was adopted. This method is similar to that used earlier for such structures as the Serre-Ponçon Dam in France. The two cofferdams are shown in section on Fig. 14. Both were eminently successful in that they permitted complete dewatering of the site on schedule with an average pumping rate of 60 liters/sec.

An additional feature, of particular interest to foundation engineers, encountered at Manicouagan 5 was the more or less accidental discovery of an extensive, flat-lying, sand-filled fissure under the right buttress of the main arch at a depth some 7 m below the planned foundation grade, and as much as 21 m below the original rock surface. This fissure had a maximum opening of about 15 cm. It followed an irregular pattern and was found to have undergone a few centimeters of horizontal displacement after the separation had occurred. This discovery made it necessary to extend the foundation excavation to a lower elevation and thus increase excavation quantities by about 12,000 cu.m. of otherwise sound rock. Following extensive investigation by borehole camera and

FIG. 12. Manicouagan 5 Dam.

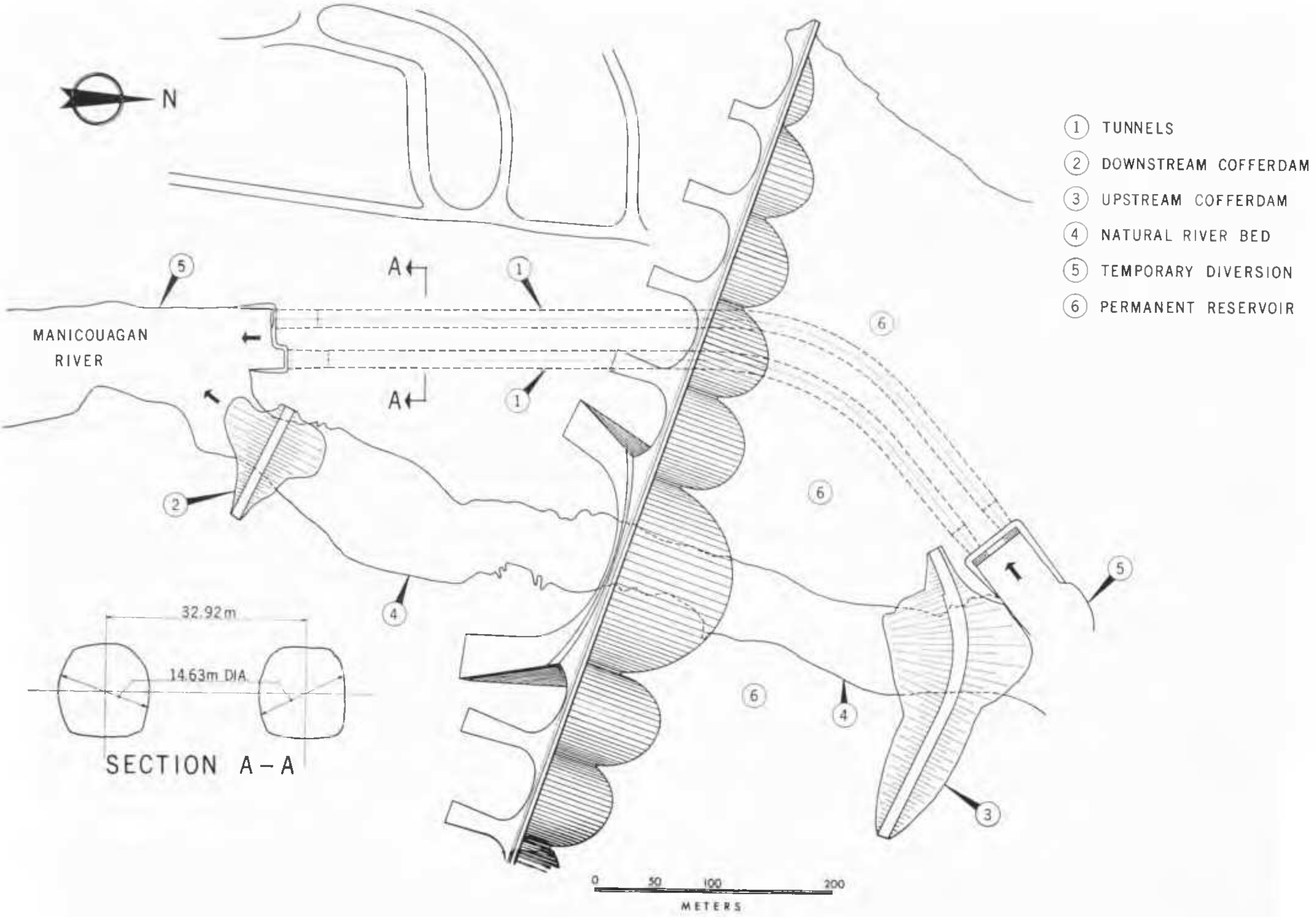

FIG. 13. Manicouagan 5 Dam—plan of right bank.

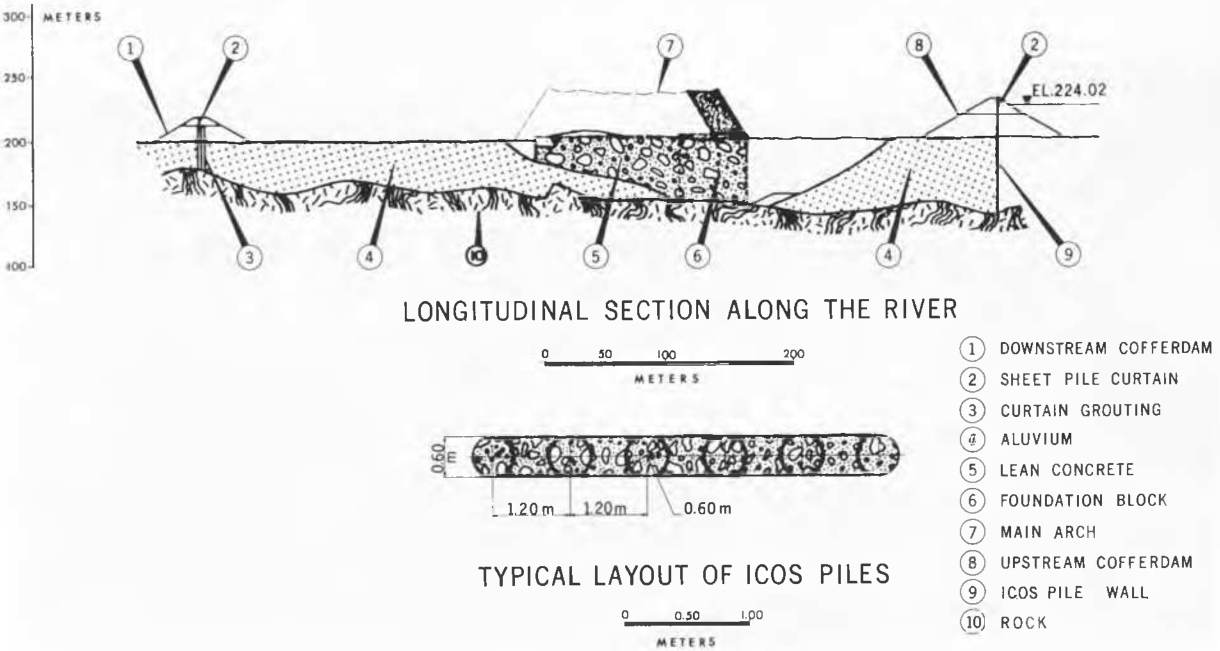

FIG. 14. Manicouagan 5 Dam—cross-sections through cofferdam and main arch.

closed circuit television, other fissures were found in the general site area, but none at a critical location.

It was noticed that the fissures tend to occur under small hills or protuberances of the bedrock. They are believed to have resulted primarily from rebound of the rock following the removal of the superimposed glacial load during one of the earlier stages of the Pleistocene epoch, when the ice is estimated to have reached a maximum depth of 3,000 m and to have resulted in a pressure of some 180 kg/sq.cm. The entry of sand into the fissures and the subsequent lateral displacement is believed to have followed during later ice ages. In this respect, the phenomenon differs from the rebound encountered at the South Saskatchewan site in Western Canada where the soft shales continue to expand and to absorb water.

The discovery of these fissures has led the engineers to doubt the reliability of diamond-core boring for detection of such weaknesses. Percussion drilling under the continuous supervision of competent inspectors was found to be much more reliable. Borehole camera and television were also of great assistance during the investigations.

Mactaquac Dam

This dam is No. 7 on Figs. 1 through 4. It is located on the St. John River in the Appalachian region about 145 river km from the Bay of Fundy. The riverbed in the vicinity of the dam is more or less at sea level; hence the gradient to the sea is flat and high tides reach to within 20 km of the site. The river flows through a channel that has been eroded to a depth of about 45 m below sea level and subsequently backfilled with a sequence of glacial, lacustrine, and alluvial deposits. The bottom 15 m of the backfill comprise a stratified sand and gravel aquifer containing water under artesian pressure. Above this aquifer there is a layer of clayey till with a maximum thickness of about 18 m, followed in succession by some 6 m of lacustrine clay and 6 m of riverbed alluvium at the surface. Bedrock of the abutments is relatively close to the surface.

The dam is being constructed as a compacted rockfill with a central impervious core of clayey till having a slight inclination as shown on Fig. 15. The maximum height will be approximately 55 m. The rockfill for the upstream and downstream slopes will consist of graywackes and slates obtained from nearby excavations and compacted with vibratory equipment. Owing to the close jointing of this rock it is expected that the resulting fill will contain a high percentage of fines, and that it can be adapted for the transition zones on either side of the impervious core by proper control of the placing operation.

The dam is being constructed in the dry between two cofferdams to be incorporated in the upstream and downstream toes. Prior to the construction of cofferdams, the entire base of the dam, inclusive of cofferdam area, is being dredged to a depth of 12 m or more to remove the alluvium and lacustrine clay and to obtain a foundation for the entire structure on the clayey till well above the underlying artesian aquifer. During the early stages of construction, and while the area between the upstream and downstream cofferdams is dewatered, it will be necessary to reduce the artesian pressure in the bottom aquifer. This reduction of pressure is being

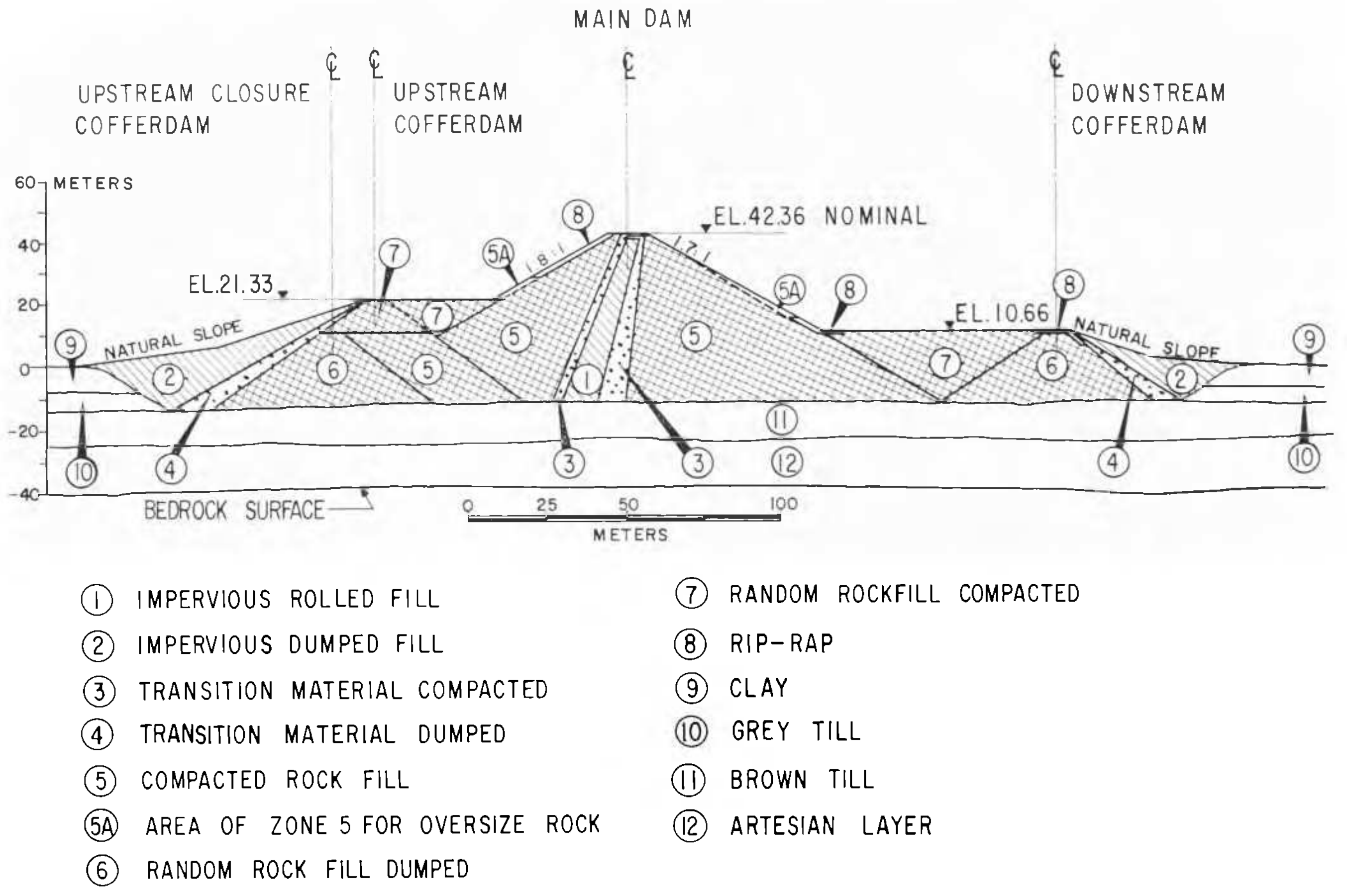

FIG. 15. Mactaquac Dam.

accomplished by the use of deep well pumps. After completion of the structure, the artesian pressure will be controlled by relief wells.

OTHER DAMS IN CANADA

The seven dams which have been described in the preceding paragraphs do not constitute a complete list of the dams currently under construction, or recently completed in Canada. They have been selected to provide a representative distribution of structures across the country and to illustrate the solutions to problems inherent with our glaciated terrain. Many dams entailing problems of equal interest have had to be omitted. There is, for example, the Mission Dam ("Three phases," 1961) on the Bridge River in the Cordillera region which was completed about three years ago and which affords an unusual example of a structure founded on a great depth of unconsolidated material in a typical valley of the Cordillera. In this case steel sheet piling was driven in a trench stabilized with bentonite slurry to cut off an upper aquifer, and the Solétanche grouting method was used to seal off a lower one. Another unusual feature was the incorporation of a sheet of polyvinyl chloride in the impervious clay blanket of the upstream face to guard against the cracking of the blanket that might result from the amount of settlement expected. Terzaghi devoted much time to this structure, and it is interesting to note that Casagrande in his foreword to a paper by Terzaghi and Lacroix (1964) says, "The design and construction of Mission Dam was the most difficult and most daring engineering project of Terzaghi's entire career. It demanded more extensive use of Terzaghi's experience and professional knowledge, and more concentrated attention and time over a period of many years, than any other single consulting assignment."

Two dams of interest have also been constructed recently on the extreme western edge of the Central Plain, namely the Waterton and the Brazeau Dams. Both are earthfill structures of more or less conventional design. One of the interesting features of the Waterton Dam is the construction of a reinforced concrete chute spillway over unconsolidated materials requiring the excavation of underlying alluvial clay and its replacement with some 9 m of pervious granular material through which a mixed clay and concrete cutoff was added. At the Brazeau Dam (Mulherin, 1963) the foundation shales were subject to rebound and swelling similar to that encountered at the South Saskatchewan Dam. This resulted in a longitudinal humping or arching of the foundation along the bed of the river and produced cracks transverse to the axis of the dam which required extensive cutoff trenching.

The Squaw Rapids Hydro-Electric Project is located on the Saskatchewan River downstream of the South Saskatchewan Project at a site where the depth to bedrock is 105 m. Hence it involves some interesting problems in the construction of massive, concrete structures on glacial till. The con-

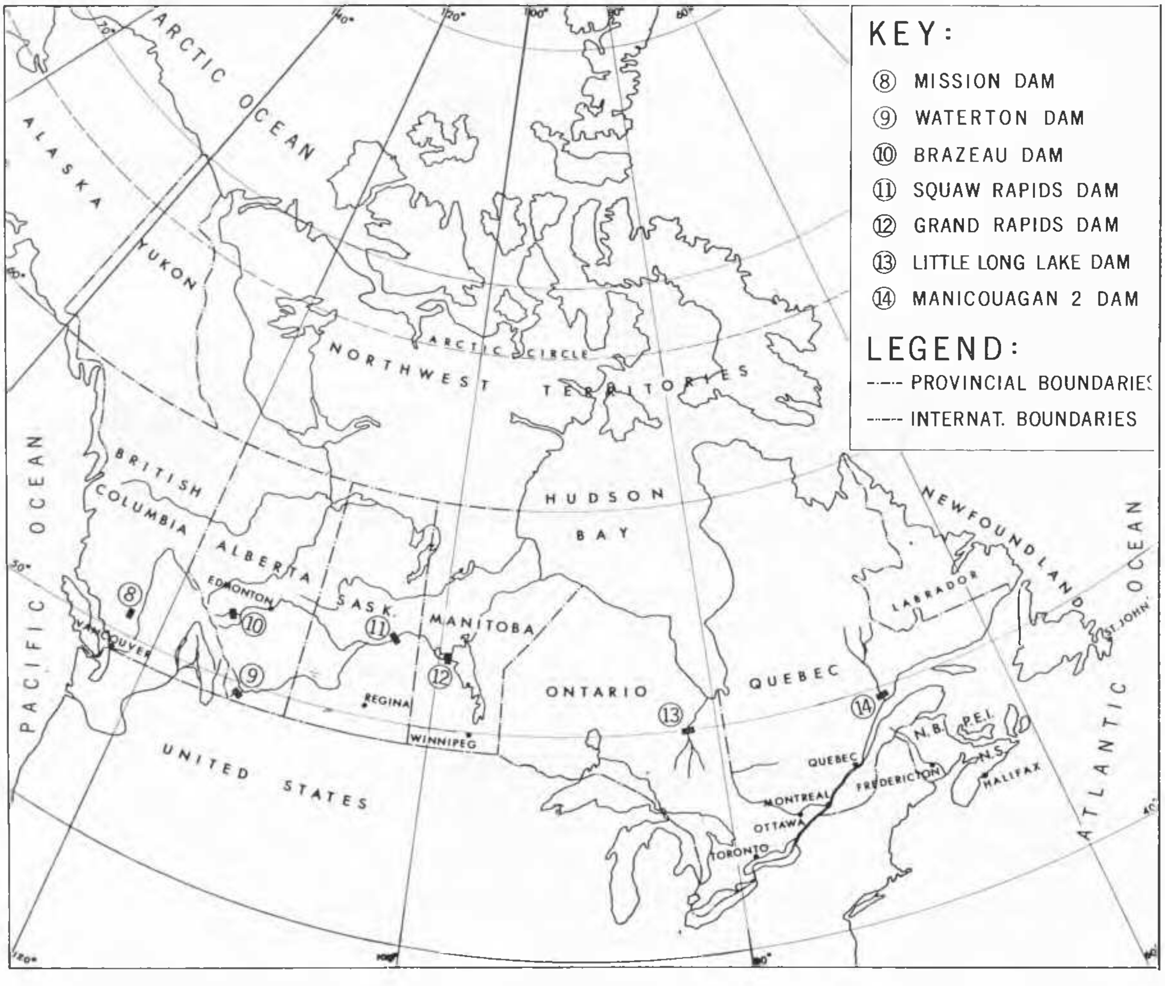

FIG. 16. Additional recent dams.

crete spillway dam, intake dam, and power station were sectionalized and articulated to provide flexibility, and extensive drainage systems were added. With ambient temperature at the site varying over a range of 83 C it has been noticed that these jointed structures are in slight but continual movement. Moreover, the seepage under them has been found to vary more or less inversely with temperature. At the spillway the seepage varies from 0.4 liters/sec in summer to 0.9 liters/sec in winter, while at the penstock intake structure it varies from 0.8 liters/sec to 2.6 liters/sec.

The Grand Rapids Generating Station (Rettie and Patterson, 1963) was completed last year at the downstream end of the Saskatchewan River where the latter discharges into Lake Winnipeg. The site is created by an escarpment of limestone and dolomite rock which rises approximately 30 m above the level of the lake in a series of benches to create the most easterly steppe of the Central Plain. The limestone rock contains numerous drainage paths; sinkholes are in evidence on the adjacent plain; and springs emerge at the base of the escarpment. Accordingly, the main problem of the dam builder at this site was to provide an impervious foundation for the 26 km of earth dykes required for the reservoir. This was accomplished by a pressure grout curtain to a maximum depth of 60 m over a length of 29 km.

The Little Long Lake Dam ("Hydro builds," 1963) is located on the Hudson Bay slope of the Canadian shield where it dams the Mattagami River for hydroelectric power. It consists of a concrete gravity structure spanning the river and flanked by approximately 8 km of earth dykes containing 2,700,000 cu.m. of material. These are conventional structures and entail no unusual difficulties, but it is interesting to note that the earthworks were completed in a 20-month period during which the contractor worked continuously on either placing or excavation of materials in spite of winter temperatures which at times fell as low as −50 C.

The Manicouagan 2 Dam is being built on the river of the same name downstream of Manicouagan 5. It is a concrete dam of the hollow-joint type 100 m high, and is scheduled for completion in 1965. Like the Manicouagan 5 Dam, it has had to be built to an exacting time schedule to meet the growing power load of the Province of Quebec, and here again one of the first problems was the rapid dewatering of the site. Fortunately, the depth of overburden in the riverbed was relatively shallow, although the water itself was 21 m deep. The problem was solved by the use of an earthfill cofferdam with a concrete membrane of the Icos-Veder type to bedrock as was done at the upstream cofferdam of Manicouagan 5.

The locations of these seven additional dams are shown on Fig. 16.

RÉSUMÉ

The most notable feature of modern Canadian dams is the preponderance of earth and rockfill structures—with preference usually given to the former, if materials are available. The reasons are obvious. Earth- and rockfills are well suited to our climate. They are not significantly affected by endless repetition of the freezing and thawing cycle. They become an integral part of the landscape and require little maintenance. In fact, an earthfill dam, if provided with adequate freeboard and spillway capacity, should have an indefinite life. Moreover, the flexibility of an earth- or rockfill dam is well suited to the unconsolidated foundations so frequently encountered with our heavily glaciated terrain. Only such a flexible type of dam would have been feasible at Mission, Arrow, Duncan Lake, or Mactaquac; and dams of rigid section would certainly have required much greater foundation excavation at Mica, Waterton, Brazeau, or South Saskatchewan than do the rock- and earthfills selected. Hence they would undoubtedly have been more expensive. An earth- or rockfill dam also lends itself to the great extension of base width so frequently necessary to develop seepage paths with hydraulic gradients of 3 to 10 per cent through pervious foundation materials.

It is also to be noted that refinements are being adopted in the design and construction of earth- and rockfills. There appears to be less use of sluicing for rockfills and greater use of vibratory equipment for their compaction, as the examples at Mica and Mactaquac indicate. This is a convenience where deep foundation dewatering problems are involved; and it facilitates cold-weather construction.

The side slopes of earthfills are being carefully related to the foundation conditions and to the component materials of the structure. At Mission, Duncan Lake, and South Saskatchewan, for example, the lower embankments have slopes so flat as to approach the horizontal; whereas at Portage Mountain, Brazeau, Squaw Rapids, Grand Rapids, and Little Long Lake, the downstream slopes vary between 2 to 1 and 2.5 to 1.

More pressure relief wells are being used to improve stability at the downstream toes of both earth- and rockfill dams. Mission, Arrow, Duncan Lake, South Saskatchewan, and Mactaquac afford excellent examples of this practice.

There is increased use of bentonite slurry to stabilize deep, cutoff excavations and thereby facilitate the placing of impervious membranes—whether the membrane be steel or impervious fill. This method was used under permanent structures at Mission and Duncan Lake, and in temporary cofferdams at Manicouagan 2 and 5.

Only in the length of construction season do earth- and rockfills appear to suffer in comparison with concrete dams, and this problem is under progressive attack. Contractors are working later in the fall of the year by careful conservation of heat in the placing of materials. Where they can work in dry, granular materials, as at Little Long Lake, they sometimes operate continuously.

As for concrete dams, only three have been referred to in this paper but one is tempted to generalize that there is a tendency to depart from the simple, mass-gravity section in favour of more sophisticated designs as a means of reducing quantities and costs. This tendency is very much in evidence at Manicouagan 2 and 5; Squaw Rapids is another example. It would appear that modern improvements in formwork are facilitating this change.

ACKNOWLEDGMENTS

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Prairie Farm Rehabilitation Administration; Squaw Rapids Dam, Saskatchewan Power Corporation and G. E. Crippen & Associates Ltd.; Little Long Lake Dam, The Hydro-Electric Power Commission of Ontario; Manicouagan 2 Dam, Quebec Hydro-Electric Commission and H. G. Acres & Company Ltd.

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