NATIONAL RESEARCH COUNCIL
CANADA

DIVISION OF BUILDING RESEARCH

EXPERIENCES WITH GROUND WATER ON CONSTRUCTION

BY

ROBERT F. LEGGET

REPRINTED FROM
PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS
JOURNAL OF THE SOIL MECHANICS AND FOUNDATIONS DIVISION
VOL. 88, NO. SM2, APRIL 1962, P. 1 - 17

TECHNICAL PAPER NO. 138

OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA

PRICE 25 CENTS JULY 1962 NRC 6846

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

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

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

3092 April, 1962 SM 2

Journal of the

SOIL MECHANICS AND FOUNDATIONS DIVISION

Proceedings of the American Society of Civil Engineers

EXPERIENCES WITH GROUND WATER ON CONSTRUCTION

By Robert F. Legget, F. ASCE[1]

SYNOPSIS

Local ground-water conditions are generally disrupted by construction operations even when accepted methods of handling ground water are used. In most cases natural conditions are restored after a structure is completed, but some engineering projects necessarily cause permanent change in previously existing ground-water conditions. Some unusual Canadian examples include the "control" of ground water at Steep Rock Iron Mines by trapping it before it reached the drained lake bed in order to obviate erosion of the lake bed deposits; the La Tuque hydroelectric development on the St. Maurice River where seepage around a large concrete dam showed itself in a small natural lake, the level of which had to be controlled by pumping; and the Aguasabon hydroelectric development on the shores of Lake Superior, where a "perched reservoir" was used as the main forebay in an area of pervious sand and gravel, glacial silt forming the lining to a natural basin in this pervious material.

INTRODUCTION

Ground water is a familiar problem on construction projects. It is frequently encountered in open excavation work. Methods for handling it by pumping from open sumps, from deep wells, or, preferably in most cases, by the use of a wellpoint system, are now accepted features of construction practice, but they must always be used with care and under expert guidance. In tunnelling operations, the presence of ground water may be troublesome and costly. If

Note.—Discussion open until September 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, Vol. 88, No. SM 2, April, 1962.

[1] Dir., Div. of Bldg. Research, Natl. Research Council, Ottawa, Canada.

pumping any of the ground water that seeps into a tunnel will not keep the work dry, grouting of the rock around the heading may prove effective; cement grout and chemical mixtures have been successfully and widely used for this purpose. In extreme cases, compressed air may be necessary to control the inflow of ground water, but "air" will always be used only as a last resort.

Ground water at the bottom of an open excavation poses no difficult question as to its occurrence; the appearance of water at the bottom of a well presents so direct a parallel that few engineers will ever be puzzled by its appearance. The very simplicity of such evidence of ground water can prove to be misleading because the control of ground water during open excavation work can be a complex and difficult operation. The presence of water in tunnelling may be so troublesome that sometimes the mere problem of controlling it distracts attention from its origin. There are on record, however, many notable examples of careful study of ground-water conditions occasioned by "wet tunnels," one of the earliest being the great work of Robert Stephenson during the construction, in 1838, of the Kilsby Tunnel, near Rugby, England.[2]

The writer has become increasingly aware of the fact that many civil engineers have little appreciation of the "geological" characteristics of ground water. One interesting, and rather human, indication of this neglect of geology is given by the number of engineers who will give serious consideration to water divining (or dowsing) without recognizing the charlatanry so often associated with this practice, whereas they will not accept the simple fact that ground water is a part of normal subsurface conditions, to be studied in the same way as the other geological features of a construction site.

The writer's purpose herein is to describe briefly some typical examples of ground-water problems encountered on construction work, each illustrative of one of the many ways in which ground water must be considered if trouble is to be avoided. It will be seen that in each case the basis of the solution to what was, or might have been, a problem was relatively simple and straight forward, after the local ground-water conditions had been recognized. It is, in fact, this very simplicity that is so often a serious impediment to the proper appreciation of the significance of ground water on construction. Construction engineers have been known to regard mere "playing about with seepage" as quite beneath their dignity, until they were faced with the serious consequence of its neglect. Something similar to this situation, later freely acknowledged, developed in the writer's own experience on one of the projects to be described.

Fortunately, a number of excellent guides to ground-water hydrology are available; some useful titles are given in the Appendix. These references show how ground water may be expected under most of the earth's surface, present either in the voids of porous materials, in the joints of more solid materials, in cavities, and in other subsurface irregularities. Replenished by rainfall soaking into the ground, and controlled by discharge through seepage on slopes and directly into water courses, through springs and (to a limited extent) by transpiration of vegetation, ground water is a dynamic geological phenomenon. Its regular movements follow the physical laws for capillary action and laminar flow.

Possibly the most important of all interferences with ground water that occurred as a result of the construction of an engineering project, graphically

---

[2] "Presidential Address," by W. K. Wallace, Proceedings, ICE, Vol. 5, January, 1956, p. 14.

illustrating this geological aspect of groundwater, is the effect that the Aswan Dam in Egypt has had on ground water in the adjacent Nubian sandstone. As early as 1898, John Ball was the first to see that the River Nile received much of its flow in its lower reaches by infiltration from the sandstone through which the river flows. When the great dam was completed (the first stage) in 1902, the rise in the water level in the reservoir area caused a reversal in the flow of this ground water. Dramatic and irrefutable evidence of this effect was provided by appreciable increases in the flow of water at distant desert oases; the oasis at Kharga has now (1962) trebled, since 1900. The significant potential influence of this ground-water condition on the proposed construction of the "High Dam" has been examined.[3,4]

Distribution of ground water will be determined, therefore, by local geological structure, continuous impermeable strata, for example, naturally forming barriers to ground-water movement. Not only will they prevent movement downward but, correspondingly, they can trap ground water in "buried" pervious strata. If such a succession of strata is inclined to the horizontal, ground water can thus be retained under hydrostatic pressure, this being the commonly described artesian or sub-artesian state of ground water. Fig. 1 shows artesian water in the middle of the Grand River, Ontario. The water jet is coming up through the casing of a test hole put down at the site of the Shand Dam after the hole had penetrated into the water-bearing Guelph dolomite, over which glacial till formed an impermeable blanket.[5] When this jet suddenly shot out of the water of the river while it was at flood level (a week or two before the photograph was taken), ground-water conditions at this construction site immediately become a matter of common job interest. The necessary graphical explanation of the water jet to the men on the job led to a general appreciation of the geology of the site that might have been difficult to achieve without such dramatic evidence.

Not only does ground water move in response to applied pressures and along suitable graded paths, but its relative position may change throughout the year with variations in rainfall, and even from year to year in response to variations in annual precipitation. Long-term observations of ground-water levels are always desirable, therefore, in any program of subsurface exploration. Correspondingly, the success of any solution to a problem with ground water on construction cannot be assured until several years have elapsed. The projects to be described were all undertaken several years ago. Results of ground-water studies in each case have been observed in the intervening years, long-term ground-water level records for the last two cases having kindly been made available for examination. In this instance, therefore, the interval between construction and this reporting is desirable, although it should be added that some unusual circumstances have made the

---

3 "Recent Developments in Nile Control," by A. A. Ahmed, Proceedings, ICE, Vol. 17, 1960, pp. 137-180.

4 "An Analytical Study of the Storage Losses in the Nile Basin, with Special Reference to Aswan Dam Reservoir and to High Dam Reservoir (Sadd-El-Aali)," by A. A. Ahmed, Proceedings, ICE, Vol. 17, pp. 181-200.

5 "Soil Mechanics at the Shand Dam," by A. W. F. McQueen and R. C. McMordie, Engineering Journal, Vol. 23, April, 1940, pp. 161-177.

interval rather longer than was really necessary for assurance as to the efficacy of the measures described.

GROUND WATER AT STEEP ROCK LAKE

Steep Rock Lake has an area of approximately 10 sq miles and was located midway between Winnipeg and the head of Lake Superior in western Ontario.

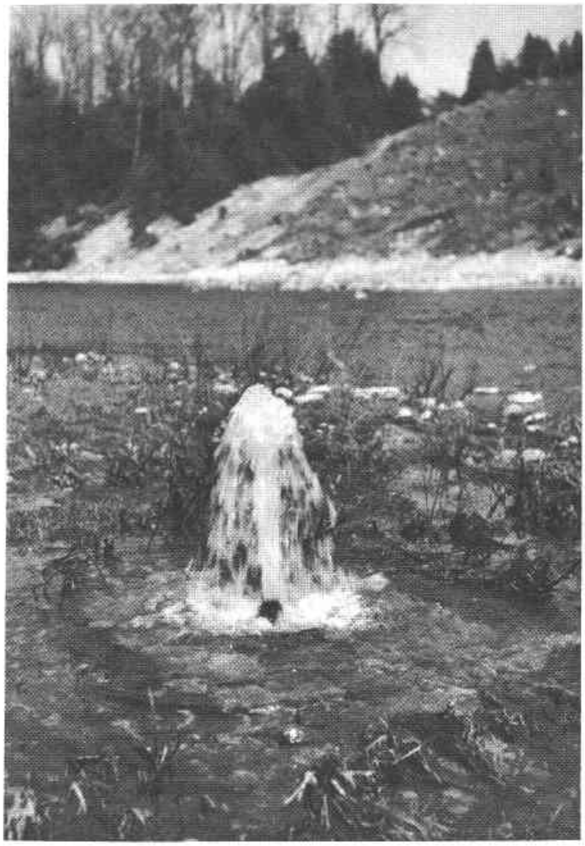

FIG. 1.—WATER UNDER ARTESIAN PRESSURE

The Seine River used to flow through it, this having been one of the original water routes to western Canada. High grade iron ore was discovered beneath the waters of the lake by geophysical prospecting. It was therefore decided to dam the lake at its two ends and pump it out in order to mine the ore, first by open-pit operations in the old lake bed and finally by underground workings beneath the open pits. The necessary civil engineering works for the river diversion were completed in 1943, and the lake drained to a depth sufficient to permit the start of open-pit mining before the end of 1944. Lowering of the lake created serious soil problems, but these were successfully overcome and mining has contined steadily since the beginning of operations. A full account of the soil problems, with references to all papers on the civil engineering aspects of the Steep Rock project, is available.[6]

Incidental to the main de-watering problems, and the associated investigations of soil stability of the lake-bed deposits, attention had to be devoted to ground water. The original lake was located in glaciated country, the surrounding shores displaying much bare rock. Soil deposits in the area draining into the lake were typical glacial deposits, of varied character. Generally, however, glacial sands and gravels predominated. Due to the geological "youth" of the area, drainage was only imperfectly developed, so that all around the lake there were such evidences of ground water as "muskegs," springs, and many signs of seepage, some of this concentrating in small streams. It was, therefore, clear that most of the precipitation of the drainage area around the lake was flowing underground, over the generally shallow bedrock surface, into the waters of the lake. It was equally clear that, as the water level in the lake was lowered, the equilibrium of the exposed soil on the sloping side banks of the original lake bed would be disturbed. Increased pore-water pressures would be developed in the newly drained soils. As the ground water seeped out along the rock surface under these now-exposed slopes, its flow might sometimes be concentrated, with possible erosion of the unstable soil.

The extensive landslides that developed all around the lake in the early stages of de-watering (especially as the frozen surface of the soil exposed during the winter's pumping gradually thawed) gave dramatic evidence of this action of "disturbed" ground water. All that could be done, in this first stage, was to let "Nature take its course." The vivid evidence of what may be called "accelerated geology" repeatedly showed the power of relatively small quantities of water. Clearly, however, every effort that could be made to divert any obvious concentrations of ground-water flow would be desirable. This was recommended to the mine authorities, and they performed a number of small diversion projects. The construction of small concrete dams across running streams adjacent to the old lake bed sufficed to create small ponds, the overflow from which, into adjacent drainage areas and away from the drained lake bed, diverted concentrated flows. This was one of the many factors that assisted in the gradual stabilization of the exposed lake bed, thus facilitating mining and associated operations.

A further reason for arranging for the "capture" of as much water flowing towards the old lake bed as possible was to prevent any concentrated flows from running over the exposed soil of the original bed deposits. It was known that these would be unconsolidated and, therefore, easily erodible. One of the larger flow concentrations could not be diverted for a few weeks at the start of the first summer's operations due to the priority of other essential work. It was allowed to flow along its original course, thus disgorging on to the lake bed deposits that were reasonably level for several hundred feet out from the old shore line before dropping off into what had been deep water.

---

6 "Soil Engineering at Steep Rock Iron Mines, Ontario, Canada," by R. F. Legget, Proceedings, ICE, Vol. 11, 1958, p. 169.

In the course of six weeks, this small flow of water, originating not far from the original shore line as an accumulation of seeping ground water, eroded a gully (Fig. 2). Before the necessary diversion work was completed, at the end of the sixth week, this gully was 36 ft deep and over 60 ft wide. The eroded soil was varved clay, with reasonable strength and a stiff consistency. Erosion to the extent noted in such material was one of the most graphic evidences that the writer has ever seen of the necessity for con-

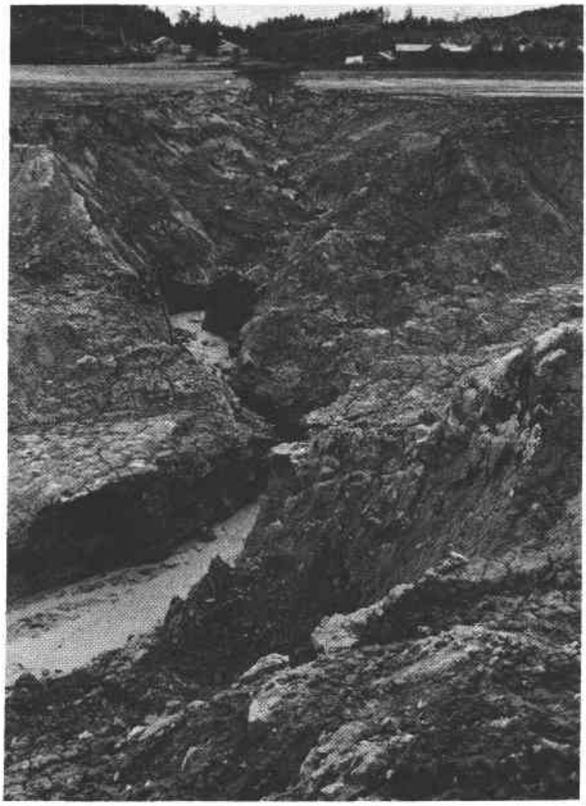

FIG. 2.—GULLYING IN DRIED-OUT BED

trolling ground water on construction works, even in such small quantity as could be seen in the small stream that caused this erosion.

GROUND WATER AND THE FIRST TORONTO SUBWAY

Canada's first subway for passenger rail traffic was constructed immediately after World War II by the Toronto Transit Commission in order to relieve what had become one of the worst traffic situations in North America. It extends from the downtown Union Station up the main traffic artery of the city for a distance of 4.6 miles. So successful has the subway proved that it is already being extended (as of 1962), as the start of a 10-yr expansion program. The lower third of the route was constructed by cut-and-cover trench excavation beneath Yonge Street; the center third on private right-of-way paralleling Yonge Street partially in open cut and partially by cut-and-cover construction; and the remaining third, also on private right-of-way, was entirely in open cut. An extensive program of subsurface exploration was performed in advance of construction; the soil and rock conditions thereby revealed are shown in Fig. 3. It will be seen that only in the upper part of the subway was sand encountered.[7]

Thirty of the original test borings were cased with perforated pipes and ground-water levels were read in them at 2-week intervals until the beginning of construction. Some variation was noted in the levels observed in the clay strata but these were purely local; the groundwater in these holes was held in the fissures of the weathered upper part of the clay and glacial till deposits. Records obtained from the holes in the sand, however, showed regular variation with local precipitation. Study of these records enabled accurate predictions to be made of the performance of the ground water when construction started. No unusual problems in the open-cut work were encountered, because the grade of the subway facilitated drainage by gravity.

There was, however, one somewhat unusual condition in the vicinity of the College Street Station (Fig. 3). It was known that trouble with "quicksand" had been encountered some years previously during the construction of the foundations for a large building at this location. As soon as test boring records were studied, the reason for this became obvious because the sand stratum forming the ground surface further up Yonge Street here dipped beneath the clay that formed the surface at College Street. The ground water in the sand was, therefore, confined by the overlying impervious clay. It was possible to estimate the sub-artesian pressure under which the ground water probably existed, a condition that readily explained the tales of "quicksand" in this locality that had been passed down in Toronto construction circles ever since the trouble with the building foundation. It was desirable to check this prediction in advance of the construction of the subway. The Toronto Transit Commission, therefore arranged for a deeper test boring to be put down from the bottom of the basement of a new building at this location; the record obtained is shown in Fig. 4. When the clay was penetrated, ground water immediately rose in the casing to within 12 in. of the calculated level. Information as to this critical ground-water condition was provided to all bidders on the main contract. It was taken into full consideration by the contractors for this part of the subway, special care being exercised in the excavation of the clay at this location. The example shows the necessity of sinking test holes to proper and sufficient depth for giving complete information about all ground-water conditions on construction sites. All too often shallow borings are thought to be sufficient.

GROUND WATER AT FORESTVILLE, QUEBEC

The Sault-au-Cochon is one of the smaller rivers flowing into the St. Lawrence on what is widely known as the "North Shore" (the south coast of the

7 "Site Investigations for Canada's First Underground Railway," by R. F. Legget and W. R. Schriever, Civil Engineering and Public Works Review, Vol. 55, 1960, pp. 73-80.

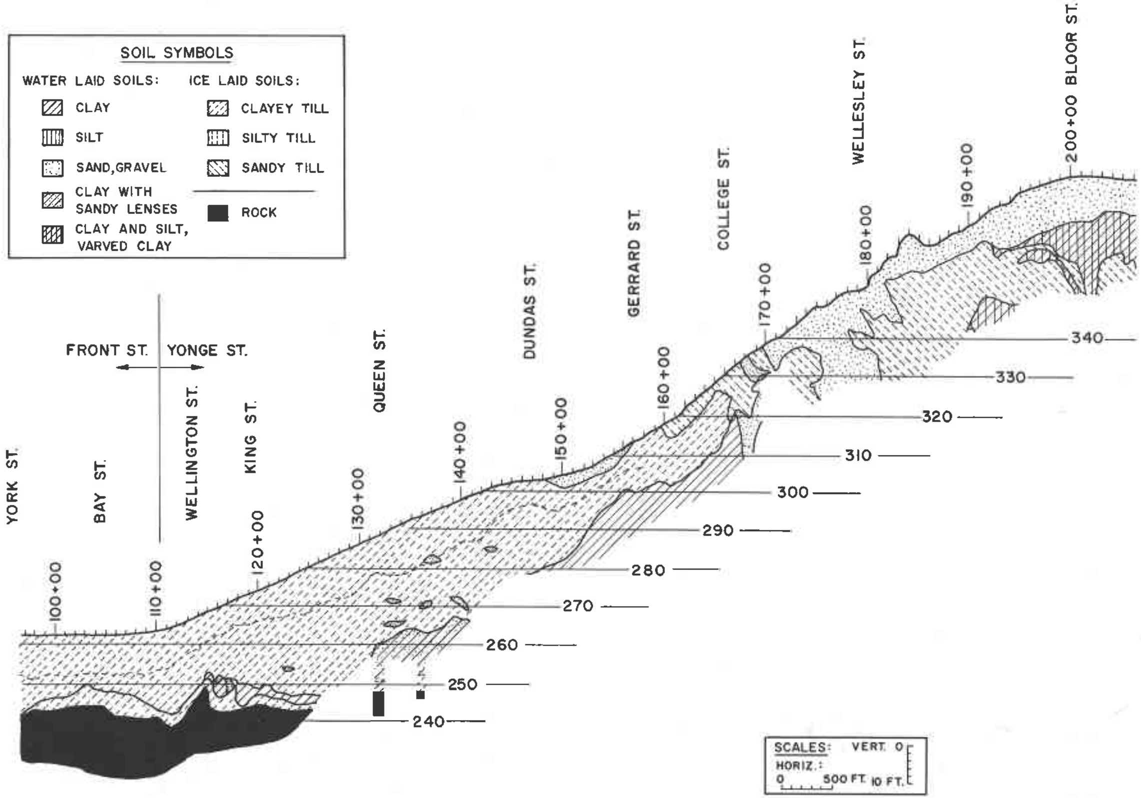

FIG. 3.—PROFILE UP THE YONGE STREET SUBWAY

Ungava-Labrador peninsula). It enters the Gulf over a singularly beautiful waterfall that, unfortunately, complicates the handling of the pulpwood regularly coming down the river. The small shipping port of Forestville, developed for the trans-shipment of this pulpwood, was therefore located approximately 1½ miles from the mouth of the river, to which it is connected by a road and a log flume, the latter taking off from a convenient ponding area above the waterfall.[8] While engaged on advising with regard to the harbor development, the writer was asked to examine the route proposed for this log flume and here encountered another ground-water problem.

Log flumes do not often come within the purview of civil engineers, but they are a singularly important part of the installations necessary for collect-

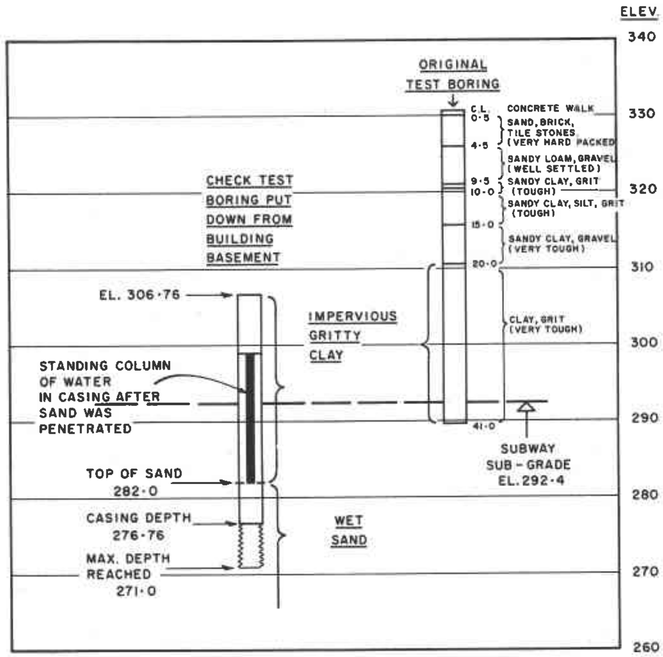

FIG. 4.—CROSS-SECTION THROUGH TEST BORING AT COLLEGE STREET

ing pulpwood from the rivers down which it is floated, and for conveying it either to the paper mill or loading berths for transportation to distant mills. At the upper end of the Forestville flume, and at its lower end adjacent to the shipping wharf, the trestles supporting the flume could be founded on bedrock. The greater part of the length of the flume, however, had to be located parallel to the access road, along a curving coastline. Much of the exposed soil was sand but some strange signs of seepage of ground water were also noticed.

8 "Development of a Pulpwood Shipping Harbour, Forestville, Quebec," by R. F. Legget, Engineering Journal, Vol. 36, October, 1953, pp. 1287-1294.

This led to a careful study of the surficial geology along the route. Wave-cut low banks below the road showed the exposures of the Leda clay that is such a distinctive feature of soils in the St. Lawrence valley. In this part of the Gulf, the clay is unusually hard and quite impervious. A few simple auger borings showed that it was continuous under the surface sand deposits, thus providing a perfect trap for any groundwater in the overlying sand. Borings showed also that, as usual, these post-glacial soil deposits were irregular, so that the possibility of movement of footings for the flume-trestles was obvious. A simple drainage system was designed to capture all ground water flowing down the main surface of the Leda clay towards the shore line, because any concentration of ground water would be liable to cause soil movement and possible trouble with the alinement of the flume. Fig. 5 illustrates the drainage system that was installed.

Interest was aroused as to the origin of the seepage evident on the slope described. At the time, the area was newly opened up and the first over-all surveys were then in progress; general maps, therefore, were not available. It was not too surprising to find, when the area beyond the crest of the slope

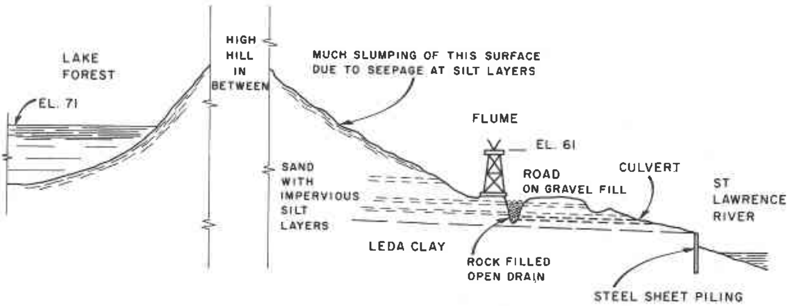

FIG. 5.—CROSS-SECTION THROUGH LOG FLUME AND ACCESS ROAD

from the shore was explored on foot, that a small lake lay immediately adjacent to the hill top, at an elevation much higher than the location of the flume. Most fortunately, this was noted just before those responsible for the logging operations decided that the lake would be helpful to them as a source of water if its level were raised a few feet. Although an accurate survey up and over the slope to the lake has not been necessary, so that only a sketch can be used to illustrate this point, Fig. 5 shows how serious any rise in the level of the lake would have been. The loggers were dissuaded from their initial plans, and the lake remains (as of 1962) at its original elevation.

Log flumes have the desirable feature of providing their own indication of any settlement of their foundations. The slightest change in the elevation of even one bent immediately shows in the water surface in the flume. It is satisfactory to record that, although now in steady operation for approximately 15 yr (as of 1962), the Forestville flume has shown no sign of movement. The entire bank along which it and the adjacent access road to the wharf are located

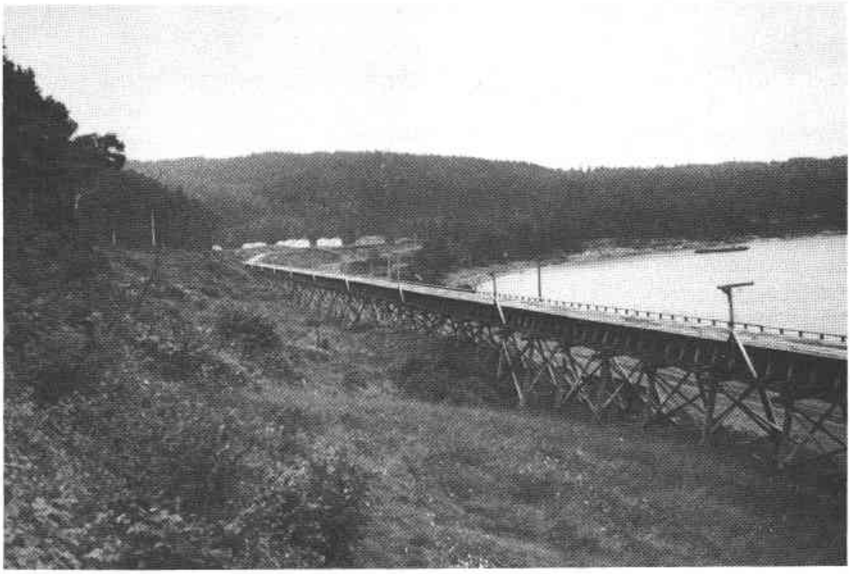

FIG. 6.—GENERAL VIEW OF THE FORESTVILLE LOG FLUME, QUEBEC

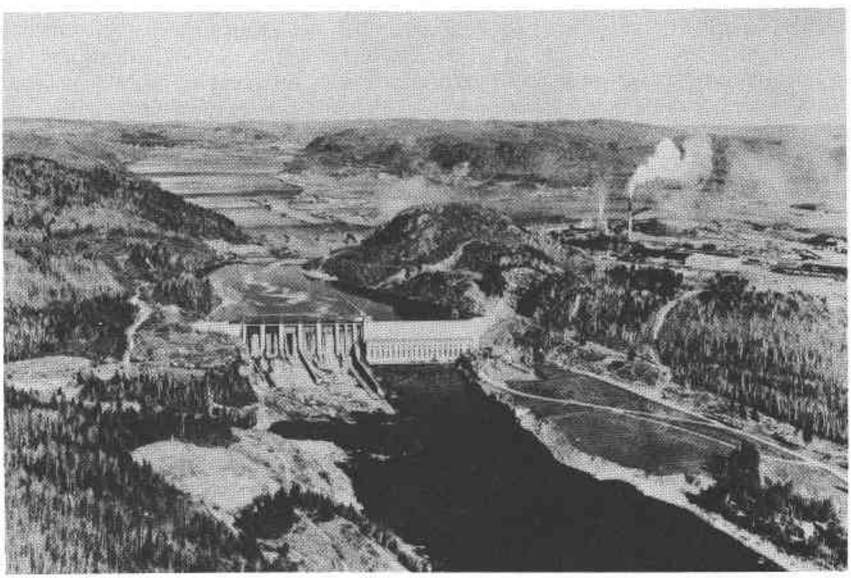

FIG. 7.—GENERAL VIEW OF THE LA TUQUE HYDROELECTRIC PROJECT

has been completely stabilized by the simple drainage system described. A general view of the Forestville log flume is shown in Fig. 6.

GROUND WATER AT THE LA TUQUE HYDROELECTRIC PROJECT, QUEBEC

A hydroelectric plant was constructed on the St. Maurice River in Quebec immediately to the west of the town of La Tuque during 1939 to 1941 with an initial capacity of 192,000 hp generated under a head of 114 ft.[9] The powerhouse is integral with the main dam that was built in what used to be a rocky gorge through which the river flowed for approximately 3/4 mile, dropping approximately 90 ft between upper and lower pools. To the west, the ground rises steeply from the original river bed, the dam finishing as a small core wall carried well into the glacial till that forms the western river bank. To the east of the powerhouse the dam abuts on to a high rock face cut into the downstream end of one of the two granite "knobs" that form an unusual feature of the local landscape. The town of La Tuque takes its name from the upstream knob. The two rock knobs stand out from a fairly level area of ground stretching approximately 1 mile to the east before steeply rising ground is again reached. The surface of this plain is approximately 60 ft above the forebay level. On it are located the town of La Tuque and a larger paper mill, as shown in Fig. 7.

This level plain continues at approximately the same elevation for some distance downstream but has a varying width. A large area immediately downstream of the powerhouse is at an elevation of 465 ft or approximately 100 ft below the level of this plain. The drop between the two areas occurs as a steeply sloping bank curved in plan to remarkably regular outline. It is known that the preglacial valley of the St. Maurice River lies under these two level areas. Geophysical exploration has disclosed the depth to bedrock to be approximately 500 ft. The old preglacial river valley is now filled with unconsolidated material derived from glacial deposits. In general, the ground consists of uniformly graded sand but some lenses of gravel also occur. The vast extent of this pervious area naturally precluded any attempt to provide a cut-off across it.

Accordingly, it was anticipated that when head-water elevation was raised to its normal operating level, there would be a substantial change in the local ground-water situation. Preliminary calculations suggested that the rise in ground-water level at the foot of the steep slope would not bring the groundwater level up to the surface level of the lower area, although it would be close to it. A series of observation wells were, therefore, installed along the foot of the slope at the outset of construction (Fig. 8). Regular readings in these wells confirmed the original calculations. After it had reached a new state of equilibrium, the ground-water level remained reasonably constant, as observed in these observation wells, located immediately to the southeast of the powerhouse.

The more unusual feature of this project is that in the center of the town of La Tuque there is a small expanse of water, long known as the Town Lake, that fills a crater-like depression in the general ground surface. Before construction of the power plant, its normal elevation was approximately 462 ft above sea level. It had no apparent inflow or outflow, the local explanation

---

[9] "Construction of Hydro-Electric Development of La Tuque," by J. A. McCrory, Engineering Journal, Vol. 24, February, 1941, pp. 54-63.

being that it was "fed by springs." This is a popular way of saying that the lake was direct evidence of the general ground-water level, disclosed in this way because of the bottom level of the depression that it filled.

It was to be expected, in view of the location of the lake, that its level might change when the water in the reservoir behind the dam rose to its final operating level. This proved to be the case, the level of the lake rising almost 5 ft soon after the main gates on the dam were first closed. This rise in water level threatened to interfere with the operation of town sewers that encircle the lake. A temporary pumping plant was installed, therefore, in order to correct the situation. The plant consisted of a 1600-gpm pump driven by a 40-hp motor discharging directly into a sewer manhole. It was found that, after

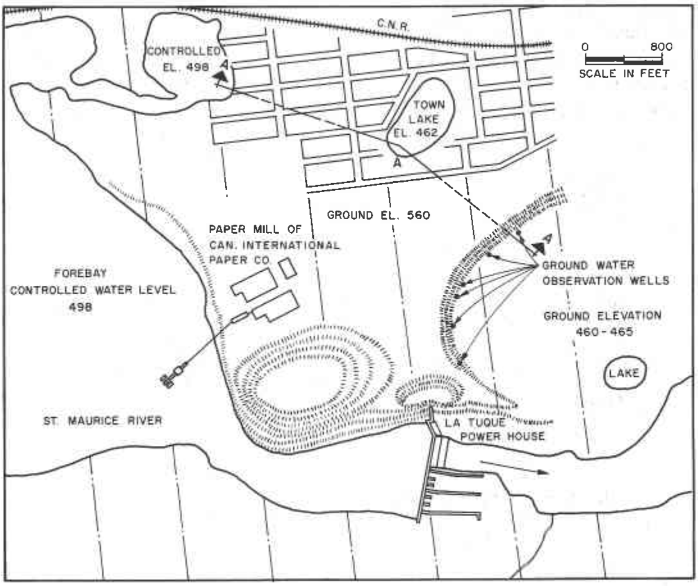

FIG. 8.—DIAGRAMMATIC PLAN OF THE LA TUQUE DEVELOPMENT

3 days of continuous pumping, the water level in the lake was reduced by approximately 2 ft, thus bringing the level of the lake down to a safe elevation in relation to the sewers.

The pumping installation was later made permanent and has operated intermittently ever since. No difficulty has been experienced (as of 1962) in keeping the lake level down to a safe elevation. Fig. 9 shows, in diagrammatic form, the over-all gradients of the ground water between the head pond, the Town Lake, and the foot of the steep slope, as they were before construction of the dam and after the rise in the head-pond level. The existence of a permanent pumping installation to correct the natural movement of ground water is unusual. The success that has attended this simple solution to what could have been a difficult problem provides yet another example of the importance of careful studies of ground water in relation to construction projects.

GROUND WATER AT THE AGUASABON HYDROELECTRIC PROJECT, ONTARIO

Between 1946 and 1948 the Hydro-Electric Power Commission of Ontario completed its Aguasabon power plant on the north shore of Lake Superior, approximately 130 miles east of Port Arthur (Fig. 10). This plant has an installed capacity of 54,000 hp generated under a head of 290 ft. Water is brought to the small powerhouse located on Terrace Bay through a 15-ft diameter tunnel leading to twin steel penstocks. The Aguasabon River enters Lake Superior approximately 2 miles to the east of the powerhouse, its water having been impounded by a concrete dam approximately $1\frac{1}{2}$ miles from the mouth. Unusual local topography results in the reservoir so formed extending not only up the river in the usual way, but flooding through a narrow gorge just above the dam into a large basin-shaped area to the west of the river, extending to

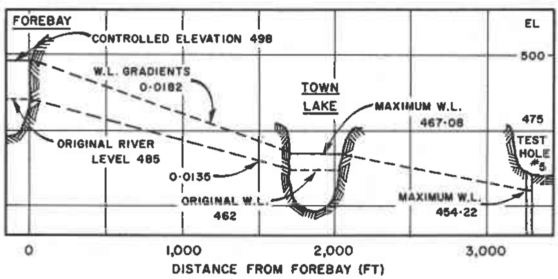

FIG. 9.—CROSS-SECTION FROM THE LA TUQUE HEAD POND TO THE OBSERVATION PIPES BELOW THE POWER HOUSE

within $\frac{1}{2}$ mile of the shore of the lake, and yet 290 ft above it (at reservoir water line). Superficial examination of local rock outcrops suggested that the ridge between the reservoir site and the lake would be of solid rock, even though covered with a mantle of soil. The usual careful preliminary test drilling of Ontario Hydro, however, penetrated to depths well below lake level along this ridge with nothing revealed but sand and gravel, the presence of many boulders eliminating any possibility of constructing a cut-off wall (even to such a depth) between the adjacent rock outcrops, and considerably complicating the drilling work.

Study of the natural basin directed attention to a small pond of water, Blue Jay Lake, in its center, a pool that could only have been retained by underlying impervious materials. The glacial history of this part of northern Ontario suggested that this might be a layer of glacial silt similar to other glacial lake deposits in this part of the Canadian Shield. Trenching around the edge of the reservoir area, and careful test drilling (with a minimum number of holes actually penetrating the blanket) revealed a continuous bed of compact and almost impervious glacial silt over the entire bed of the basin, extending, most fortunately, approximately to the intended top water level for the reservoir. Tests were made to determine by penetration the depth of the silt layer. Where this was studied it was found to be a relatively few feet, thinning out towards its upper edge. With the knowledge of this natural reservoir lining, and assuming that it was continuous, planning of the project could be completed.

The plant was built; the reservoir was filled. There was a slight increase in the level of the ground water in the sand and gravel almost 300 ft beneath

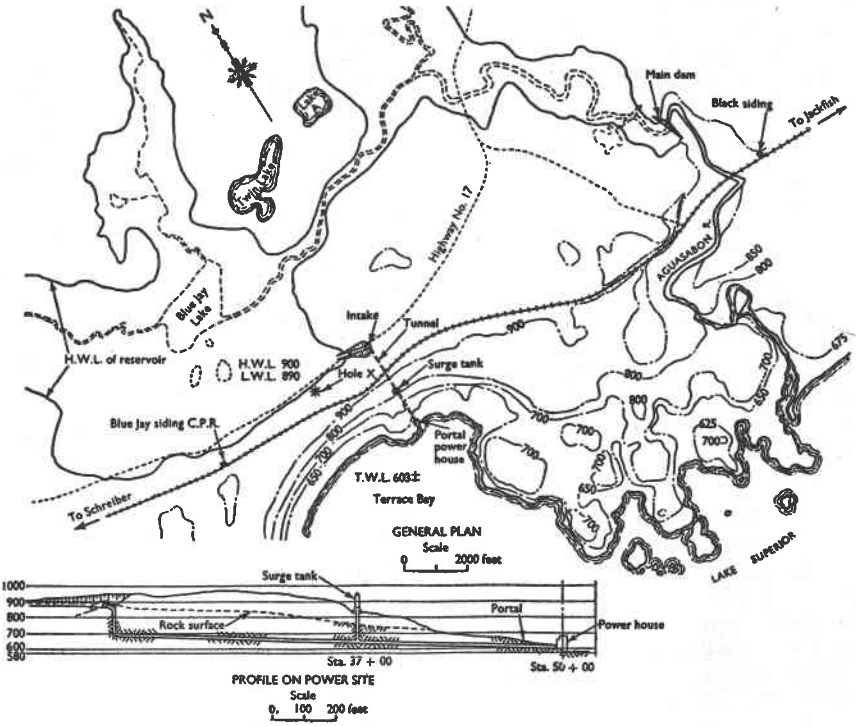

FIG. 10.—GENERAL PLAN OF THE AGUASABON HYDROELECTRIC PROJECT

the reservoir, but this gradually levelled off and the plant has been in continuous operation ever since its opening, dependent for its water supply on this natural "perched" reservoir.[10]

CONCLUSIONS

The foregoing examples suggest some simple conclusions that may be presented in the form of suggestions with regard to the necessary study of ground

10 "A 'Perched' Reservoir in Northern Ontario, Canada," by R. F. Legget, Géotechnique, Vol. 3, June, 1953, pp. 259-265.

water in relation to construction operations:

1. Investigation of ground-water conditions must be an integral part of all subsurface investigations of sites to be used for civil engineering projects. Observations of ground-water levels, seepage, and associated phenomena should always be correlated, as subsurface investigations continue, with the developing picture of the local geology.

2. In all investigations of ground-water conditions, the dynamic character of ground water must be kept in mind, both with regard to movement of ground water and the fact that ground-water levels will almost certainly be found to vary throughout the year and possibly also from year to year. Recordings of ground-water level variations should therefore, be made for the longest possible period, and certainly for never less than one full year.

3. Because of the dynamic aspect of ground water, investigations of ground-water conditions should not be restricted to the building site if there is the slightest chance of construction operations affecting or being affected by ground-water conditions removed some distance from the site itself.

4. In all such work the three-dimensional aspect of the problem should be kept in mind because sometimes this will profoundly affect the significance of individual observations; this may frequently be conveniently done by using three-dimensional peg models.

5. The dependence of ground water on rainfall should always be kept in mind. In interpreting their inter-relationship, the concept of ground-water depletion as developed[11] by C. W. Thornthwaite will be found to be a powerful tool.

6. Following the completion of civil engineering works that have been influenced by, or are liable to influence, local ground-water conditions, continued inspection for a period of several years following the completion of the work will always be essential.

ACKNOWLEDGMENTS

The writer is indebted to those responsible for the projects mentioned, with whom he had the pleasure of working, for permission to mention their work in this paper; in particular, M. S. Fotheringham, President and General Manager of Steep Rock Iron Mines Ltd.; W. H. Pattterson, General Manager, formerly Chief Engineer, Subway Construction, Toronto Transit Commission; J. O'Halloran, Chief Engineer, Anglo Canadian Pulp and Paper Mills, Ltd.; and Otto Holden, F. ASCE, lately Chief Engineer, Hydro-Electric Power Commission of Ontario (now retired). The writer is also indebted to Richard E. Heartz, F. ASCE, Chairman of the Board of the Shawinigan Engineering Co., Ltd., for permission to describe the La Tuque example, which the writer has had the privilege of visiting and studying.

11 "An Approach Toward a Rational Classification of Climate," by C. W. Thornthwaite, Geographical Review, Vol. 38, 1948, pp. 55-94.

APPENDIX.—ADDITIONAL REFERENCES

1. "Applied Hydrology," by R. K. Linsley, M. A. Kohler, and J. L. H. Paulhus, McGraw-Hill Book Co., Inc., New York, N. Y., 1949.

2. "Hydrology for Engineers," by R. K. Linsley, M. A. Kohler, and J. L. H. Paulhus, McGraw-Hill Book Co., Inc., New York, New York, 1958.

3. "The Occurrence of Groundwater in the United States, with a Discussion of Principles," by O. E. Meinzer, Water Supply Paper No. 489, Geol. Survey, U. S. Dept. of the Interior, Washington, D. C. (reprinted), 1923.

4. "Plants as Indicators of Groundwater," by O. E. Meinzer, Water Supply Paper No. 577, Geol. Survey, U. S. Dept. of the Interior, Washington, D. C., 1927.

5. "Ground Water Hydrology," by D. K. Todd, John Wiley and Sons, Inc., New York, N. Y. 1959.

6. "Ground Water," by C. F. Tolman, McGraw-Hill Book Co., Inc., New York, N. Y., 1937.

7. "Methods for Determining Permeability of Water-Bearing Materials," by L. K. Wenzel, Paper No. 887, Geol. Survey, U. D. Dept. of the Interior, Washington, D. C., 1942.

8. "Hydrology," by C. O. Wisler and E. F. Brater, John Wiley and Sons, Inc., New York, N. Y., 1959.