Postconstruction Deformations of Rockfill Dams

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Abstract: Postconstruction deformations of some rockfill dams with a slightly inclined or central till (moraine) core are presented. Although deformation still continues, even 30 years after dam construction, for all practical purposes the settlement could be nevertheless considered to cease 36 months following the end of construction. The crest settlement reflects the core compression, which is relatively low, while the downstream rockfill shoulders exhibit much higher settlements. The maximum settlement expressed as a percentage of height (%H) does not always concur with the maximum measured settlement value or with the maximum fill height. Depending on the valley cross section (width), an arching phenomenon can develop and push the maximum %H towards the abutments. Horizontal deflection downstream also expressed as a percentage of the height of the dam crest could reach 1.5–5.0 times the settlement value. The effect of impounding is illustrated by a differential deformation (settlement and deflection) of the upstream and downstream edge of the crest, inducing a progressive spreading (widening) of the crest (danger of longitudinal fissuration). Settlement and deflection envelope curves based on the values recorded by the analyzed structures could be used as a quick tool for monitoring the future behavior of dams and dikes.

Introduction

Monitoring the deformations of a rockfill dam is one of the main tools for obtaining a reliable assessment of its stability and safety. Rockfill dams continue to deform long after their construction has been completed, although at an ever-decreasing rate. Initially large or unexpected movements may be the only indication of potential problems with the structure. Thus the development of a prediction method that permits evaluation of future deformations and comparison of these values with those observed could be a very valuable safety monitoring device.

Technical literature on rockfill-dam deformation abounds. Lawton and Lester (2), for example, following the analysis of 11 dams built between 1925 and 1964, concluded that settlement is a function of the height, H, and can be expressed as $S = 0.001\ H^{3/2}$, while the horizontal deflection of the crest is about 50% of its settlement. These authors also observed that for dams with an impervious upstream facing and a relatively rapid reservoir impounding, up to 85% of the settlement takes place in the first year. For dams with impervious cores and slower impounding, up to 50% of the settlement is reached in the first year.

Analyzing the behavior of 14 rockfill dams, Sowers, et al. (7) recorded settlements of 0.25–1% of height, 10 years after construction. The settlement curves are almost linear, with log times similar to those for the secondary consolidation of soils. Sowers, et al. (7) propose the correlation:

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$$\Delta H = \alpha(\log t_2 - \log t_1) \quad (1)$$

for computing the settlement (expressed as a percentage of the height) that occurred between times t_1 and t_2 from the beginning of the period of settlement; α expresses the rate of decrease, which varies between 0.2 and 0.7 for the structures analyzed. They also noted that the magnitude of the settlement is related neither to the height nor to the dam or rockfill characteristics but to the dam construction method.

Lately, Clements (1) analyzed 68 structures and developed a new approach to evaluate their deformation. As an alternative to simple empirical relationships with discrete solutions, Clements recommends a comparative prediction approach that recognizes the large number of factors influencing dam behavior and takes account of the scatter of the data. The crest-settlement and deflection envelopes established from the 68 structures surveyed provide a quick estimate of the expected range of movements for a given design cross section. The author warns, however, that "due to the wide range of values, specific displacements cannot be calculated and therefore any results taken from these curves must be considered a first approximation." He also claims that better predictions can be obtained using data from dams with similar characteristics.

Hydro-Québec has been involved in the construction of major water-retaining structures for a long time now, and owns and operates a large number of dams. In 1985 it therefore undertook an extensive study of the deformation of its rockfill dams built after 1950 in order to obtain: (1) Better prediction of future deformations of rockfill dams and, consequently, better assessment of their safety; and (2) improved design criteria for future rockfill dams (freeboard evaluation, camber, etc.).

The results of this study reveal new aspects of rockfill deformation such as differential crest deformation, effect of the embankment arching on deformation, etc., as will be described in the following.

Main Characteristics of Structures Analyzed

Fifteen rockfill dams and dikes sited directly on a rock foundation and ranging in height from 30–500 ft (10–168 m) were analyzed for the present study. The main characteristics of these structures and their construction are shown in Table 1 and Figs. 1 to 3. A review of this data shows:

1. Of the 15 structures studied, ten dams and dikes have slightly inclined cores, two are sloping-core structures, and two have central cores; one structure is a concrete-faced rockfill dam.
2. The core of all 15 structures consists of compacted till (moraine) material.
3. The rockfill shoulders of the dams and dikes were placed in lifts of various thickness and compacted with mechanical equipment (except Bersimis 1 and Desroches dams, where placement was by dumping only).
4. The rockfill, random quarry material, was generally of good quality and placed without any treatment, except at Bersimis 1 and Desroches where it was sluiced, and Outardes 4 (dams 1 and 2) where it was passed

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TABLE 1.—Characteristics of Structures Analyzed

Structure (1)	Height, ft (m) (2)	Slopes U/S (3)	Slopes D/S (4)	Completion Date Construction (5)	Completion Date Impounding (6)	Core type (7)	Type rock (8)	Construction method (9)	Reference figure (10)
(a) Manicouagan Area									
Outardes 4: Dam 1	400 (122.0)	1:1.85	1:1.75	1968	1970	Slightly inclined 0.5:1 0.25:1	Gabbroic anorthosite	Compacted in lifts of 75–120 cm with 10-t vibratory rollers	1a
Outardes 4: Dam 2	300 (110.0)	1:1.85	1:1.75	1968	1970				1a
Outardes 4: Dam 3	82 (25.0)	1:1.85	1:1.75	1968	1970				1a
Bersimis	200 (61.0)	1:2.5	1:1.4	1955	1957	Sloping 1:1.46 1:1.38	Granitic gneiss	Dumped and sluiced	1b
Desroches	200 (61.0)	1:2.5	1:1.4	1955	1957				1b
Outardes 2: Main dam	180 (55.0)	1:1.4	1:1.4	1978	1978	Concrete facing	Gneiss	Compacted in lifts of 75–120 cm with 10-t vibratory rollers	
(b) James Bay Area									
LG-2 Main dam	550 (168.0)	1:1.8	1:1.6	1978	1979	Slightly inclined	Granitic gneiss	Compacted in lifts of 90–180 cm with 10-t vibratory rollers	2
LG-2 Dyke D-5	216 (66.0)	1:1.8	1:1.6	1978	1979	0.5:1 0.1:1			3a
D-7	180 (55.0)	1:1.8	1:1.6	1978	1979	0.7:1 0.4:1			3a
D-8	98 (30.0)	1:1.8	1:1.6	1978	1979	0.7:1 0.4:1			3a
D-9	210 (64.0)	1:1.8	1:1.6	1978	1979	0.7:1 0.4:1			3a
LG-3 North dam	305 (93.0)	1:1.7	1:1.6			Slightly inclined 0.6:1 0.2:1 Central 0.25:1			3a
South dam	305 (93.0)	1:1.7	1:1.6						3b
Caniapiscau KA-3	177 (54.0)	1:1.7	1:1.6	1980	1984				3b
KA-5	155 (47.0)	1:1.7	1:1.65	1981	1984				3b

over a grizzly to eliminate grain sizes less than 6 in. (150 mm) in diameter.

Post-Construction Deformation

Settlement.—The maximum values recorded for postconstruction crest settlement (expressed as a percentage of height) are shown in Figs. 4–7 (settlements versus logtime). The reference date (zero time) is the date of the first survey of the observation points, which was carried out immediately after their installation, i.e., very shortly after the end of construction. The settlement of the downstream rockfill shoulders of some of the dams is shown in Fig. 8. However, since the reference dates of the survey points on the downstream slopes do not coincide with the end-of-construction date, these points could have been installed many months, even more than a year, before construction was completed.

Analysis of these figures shows that:

1. The settlement curves (settlement/unit height versus log time) are not always a linear function of log time; in fact, in many cases, they

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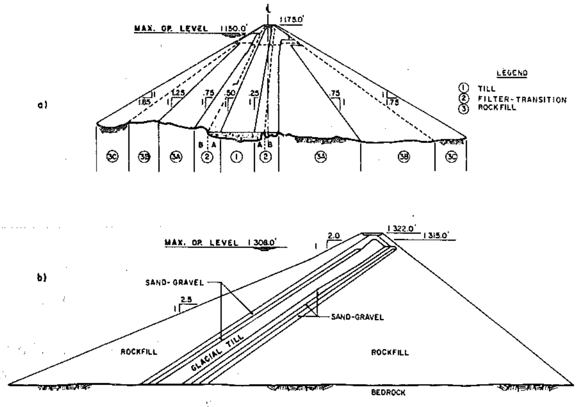

FIG. 1.—Typical Cross Section of Rockfill Dams: (*a*) Outardes 4-Type Dams; (*b*) Bersimis and Desroches Type Dams

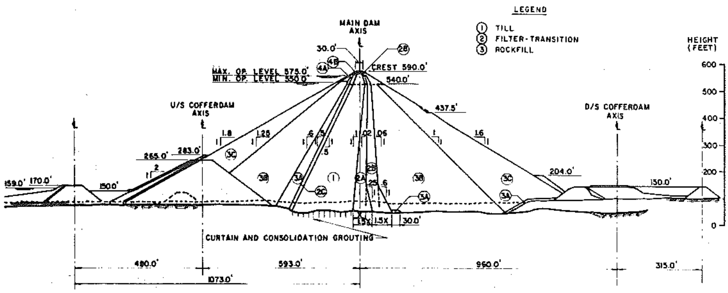

FIG. 2.—Typical Cross Section of James Bay LG-2 Dam

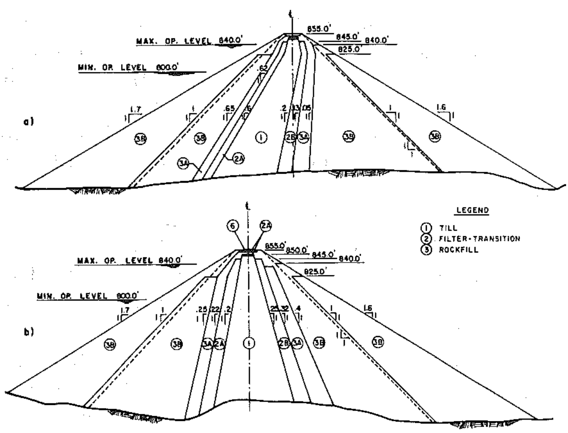

FIG. 3.—Typical Cross Section of Rockfill Dams (James Bay Area): (*a*) Slightly Inclined Core; (*b*) Central Core

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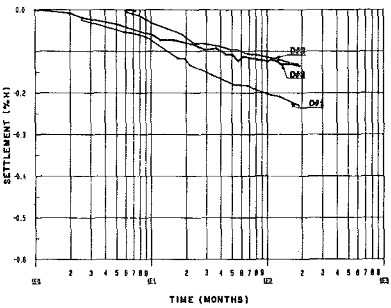

FIG. 4.—Crest Settlement versus Log Time, Outardes 4 Dams

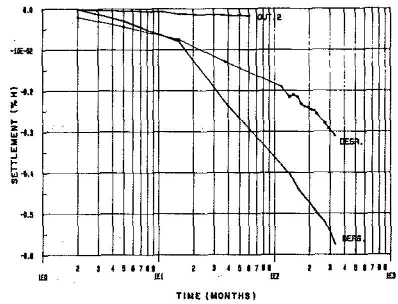

FIG. 5.—Crest Settlement versus Log Time, Bersimis, Desroches, and Outardes 2 Dams

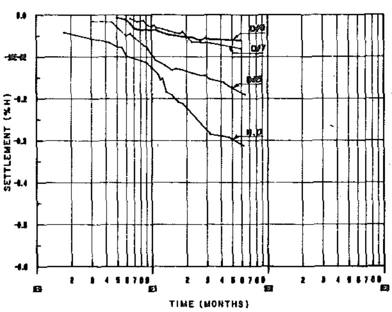

FIG. 6.—Crest Settlement versus Log Time, Lg-2 Main Dam and Dikes

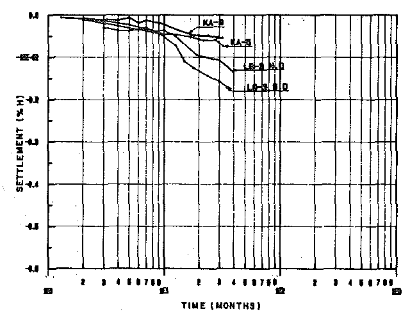

FIG. 7.—Crest Settlement versus Log Time, James Bay Area Dams

resemble classical soil-consolidation curves. They reveal three stages of settlement: initial development of a small settlement, followed by a substantial increase in the settlement and, finally, a continuous decrease of the settlement rate, asymptotically, towards the final value. The duration of the first stage is approximately 6–10 months while the second stage, which comprises the major part of the settlement and is probably related to the impounding process, ends 24–30 months after construction is completed.

2. Considering for practical purposes that total settlement is reached when the annual settlement is less than 0.02% *H*, then the time taken to reach this value by the 15 dams and dikes analyzed is about 24–30 months (except for Bersimis and Desroches dams, where the sluiced rockfill was placed by dumping only).

3. With the exception of LG-2 main dam and Bersimis 1 and Desroches dams, the total crest settlement seems to remain below 0.3% *H* during the first ten years of operation (evaluated by extrapolation). The maximum crest settlement of the LG-2 dam reached 0.5% *H*, while for Bersimis and Desroches dams settlements of 0.55% *H* and 0.3% *H*, respectively, have been recorded so far.

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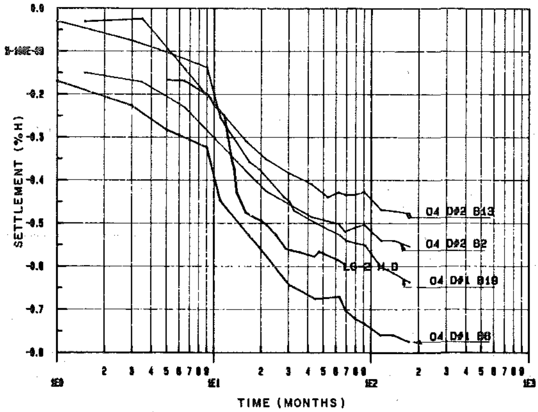

FIG. 8.—Downstream Shoulders Settlement versus Log Time, Outardes 4 and LG-2 Main Dams

It should be pointed out that during the impounding of the LG-2 reservoir, the upper part of the upstream embankment sustained a number of small, superficial slides, which led to a settlement of up to 12 in. (300 mm) on the upstream side of the dam crest. The sliding began six months after the end of construction (June, 1979) when the reservoir level had reached elevation 150 m, i.e., about 90% of its final level (4). The slides are situated between chaining 44 + 00 and 56 + 00. As shown on the settlement versus time curves (Fig. 9), survey points #23 and #24 (installed at chaining 48 + 50 and 52 + 75) exhibit a breaking point around June, 1979. Subsequently, between June and December, 1979, a significant increase in the settlement rate can be observed. Extrapolation of the settlement rate before June, 1979 beyond the breaking point and analogy with the curves for the adjacent points #25 and #26 (not affected by the slides) allow a corrected curve (marked 24 COR in Fig. 9)

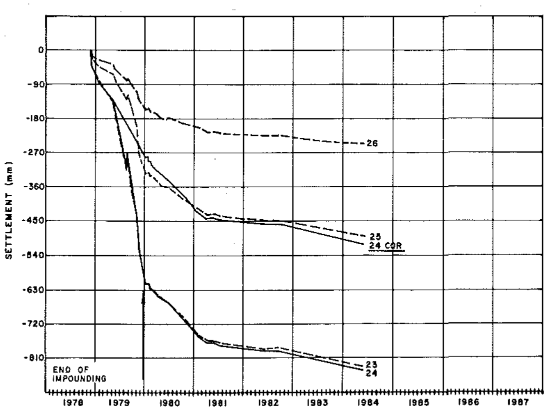

FIG. 9.—Corrected Settlement Values of LG-2 Main Dam Crest

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to be drawn, which should express more realistically the crest settlement normally reached without these accidental slides (about 0.3% H after six years). (Note: The correction is made only for the period June–December, 1979.)

4. The maximum values recorded do not always reflect the maximum settlement per unit height. As a matter of fact, analysis of Outardes 4 dams 1, 2, and 3 shows that the presence of an arching phenomenon across the river valley displaced the maximum settlement/unit height towards the rock abutments. Thus the maximum settlement/unit height concurs neither with the maximum height of the embankment nor with the measured maximum settlement (Figs. 10 and 11). Five years after the end of construction, the maximum settlement/unit height is 0.28% H and 0.13% H for dams 1 and 2, respectively, while ten years later it had reached 0.36% and 0.175% H. The settlement at the maximum height of the fill is 0.22% H and 0.12% H after 15 years of operation. The relatively wide valleys at the James Bay dam sites (Fig. 12) do not favor the development of a similar arching phenomenon.

5. The settlement of the survey points on the crest of dams with a central or slightly inclined core does not reflect the settlement of the

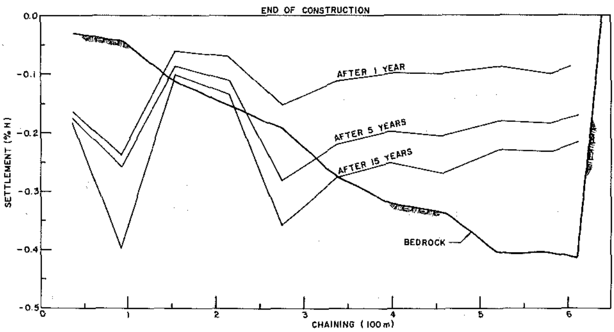

FIG. 10.—Crest Settlement Variations along Longitudinal Axis, Outardes 4 Dam 1

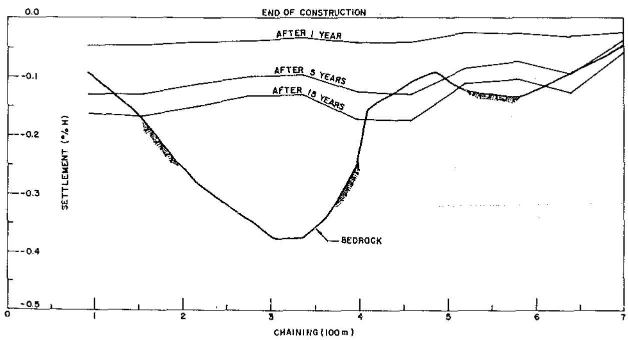

FIG. 11.—Crest Settlement Variations along Longitudinal Axis, Outardes 4 Dam 2

rockfill. As shown in Fig. 8, the survey points on the downstream slope exhibit settlements considerably higher than those on the crest. Even if the reference date is made to be identical with that of the crest points, the settlement of the downstream rockfill is still more marked than that of the crest (Fig. 13). It seems that for central or slightly-inclined-core dams, the crest settlement is mainly an expression of the core compression, and thus does not represent a characteristic feature of the rockfill's deformation. The cores, as mentioned above, consist of well-compacted morain material and are consequently less compressible than rockfill. The crests of the LG-2 main dam and the Outardes 4 dams indicate a settlement of 0.2–0.25% *H*, while on the downstream rockfill shoulders settlement reaches 0.5–0.7% *H*. Even if the reference dates were identical, the downstream-shoulder settlement is still about 0.25–0.45% *H* (Fig. 13).

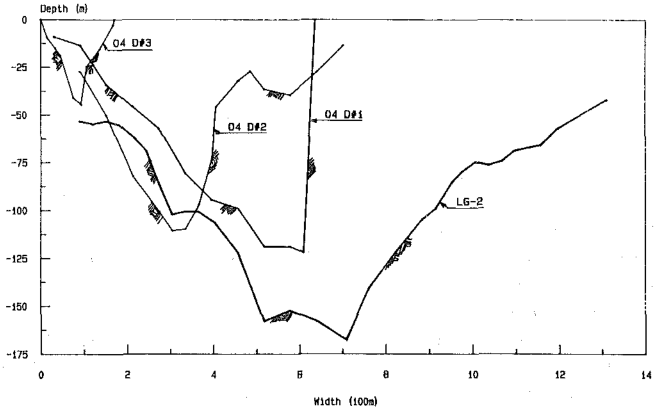

FIG. 12.—Cross Section of Outardes 4 and LG-2 Dams Valleys

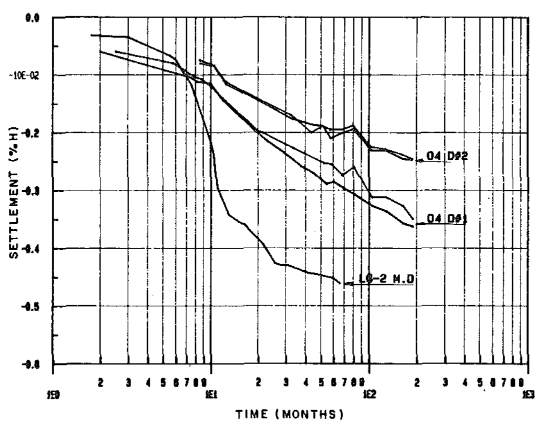

FIG. 13.—Settlement of Downstream Shoulders with Respect to Crests Reference Dates

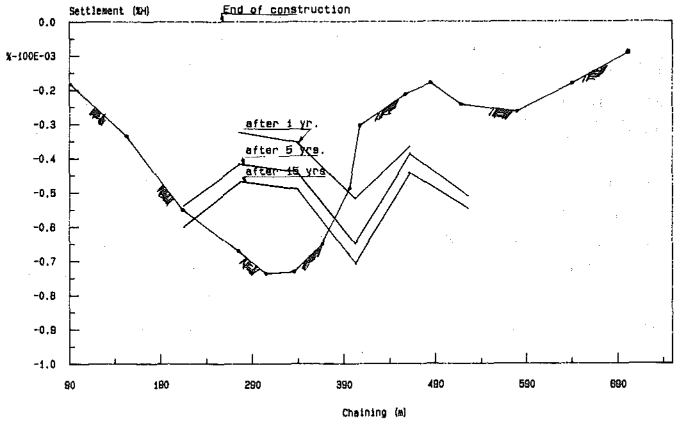

FIG. 14.—Arching Phenomenon in Downstream Shoulders

It should be mentioned here that the arching phenomenon also affects the downstream shoulders (Fig. 14).

6. The relatively high settlement values recorded at Bersimis and Desroches (0.55% and 0.3% H) could possibly be explained by the lack of compaction at the placement stage of construction. It should also be pointed out that these two dams have inclined cores, which means that the values recorded represent the real settlement of the rockfill.

However, the difference in the settlement of the Bersimis 1 and Desroches dam crests (built under similar conditions and from identical material) is difficult to explain. Analysis of Fig. 5 shows that 16–18 months after the end of construction, the rate of settlement of Bersimis 1 dam

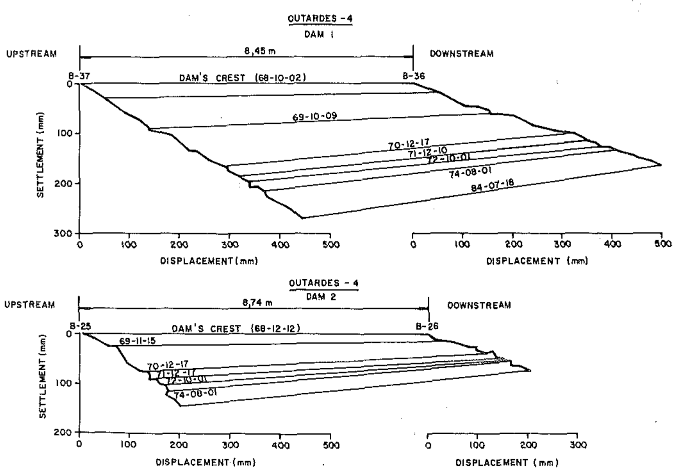

FIG. 15.—Differential Deformations (Settlement and Deflection) of Outardes 4 Dam 1 and Dam 2 Crests

increased at a substantial rate that has remained practically unchanged. The same increase, but at a much lower rate, was also detected for Desroches dam. It should also be noted that lately (120–125 months after the end of construction) another slight increase in the rate of settlement has been detected (Fig. 5).

7. The effects of impounding on rockfill-dam deformation is clearly shown in Fig. 15, which shows the high differential settlement between the upstream and downstream edges of the crest of Outardes 4 dams 1 and 2.

Horizontal Deflection.—The horizontal deflection of the crests in the downstream direction is shown in Figs. 16 and 17. The deflection is about 1.5–5 times higher than the corresponding settlement, with the excep-

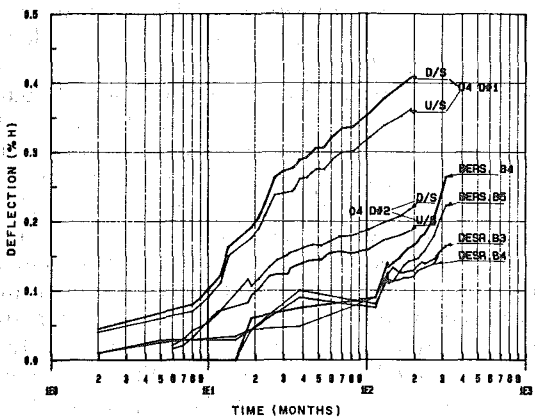

FIG. 16.—Horizontal Deflection of Crest, Outardes 4, Bersimis, and Desroches Dams

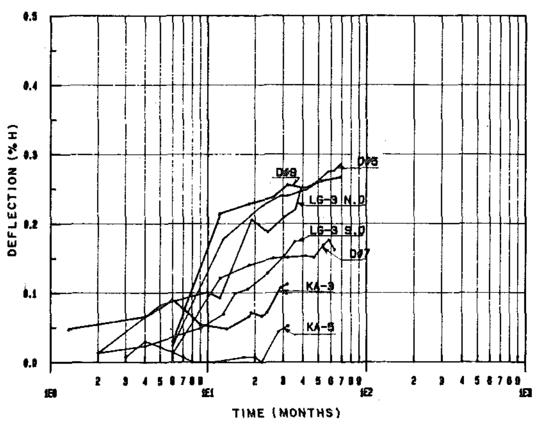

FIG. 17.—Horizontal Deflection of Crest, James Bay Area Dams and Dikes

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tion of Bersimis and Desroches dams, where it is about 50% of the settlement (range of variation 30–60%). To explain this discrepancy, the following phenomena should be considered.

1. As mentioned above, the settlement reflects the compressibility of the core (moraine), which is relatively small, while for the Bersimis and Desroches dams it indicates the compression of the rockfill. Since these are sited directly on bedrock, no foundation settlement can be considered.

2. The deflection produced by the reservoir's water load should be more significant for more rigid and imprevious structures, thus the central or slightly inclined moraine cores would exhibit a higher deflection than the relatively more compressible rockfill mass. As a result, the deflection/settlement ratio reaches relatively high values.

This behavior seems to be confirmed by data presented by Lawton and Lester (2) and Clemens (1). In both papers, the settlement of the dam crest is quite high (between 0.25–1% *H*) as compared with the value of less than 0.3% recorded for by Hydro-Québec's dams (except Bersimis and Desroches). Thus the deflection/settlement ratio is low. The effect of compaction and the compression of the foundation (where the dam is not sited directly on bedrock) could also influence this ratio. While the dams considered in the present paper were built in the last 10–20 years, with advanced equipment and compaction techniques, the structures presented by the above mentioned authors are mainly 25 years old or more, and in many cases the rockfill was placed by dumping only.

A differential deflection between the upstream and downstream edges of the crest was recorded at Outardes 4 dams which were the only ones with survey points installed on both sides of the crest (Fig. 15). This behavior seems to indicate a progressive widening of the crest and, thus, the possible development of longitudinal cracks. The data given in Fig. 15 show a spread of 2.5 in. (60 mm) at dam 1, and 1.5 in. (37 mm) at dam 2, which represent respectively 0.71% and 0.41% of the distance

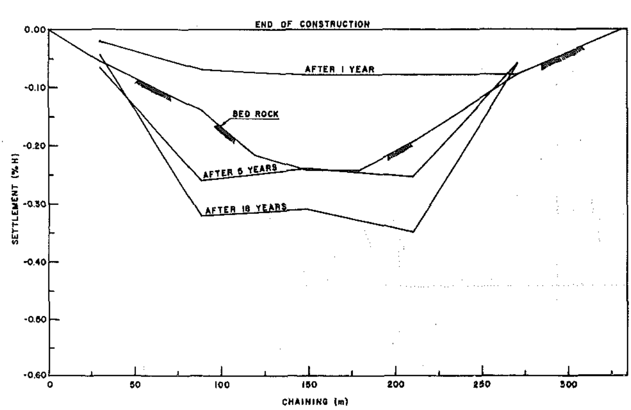

FIG. 18.—Arching Phenomenon at Desroches Dam

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between the survey points. It should be mentioned that this spread measured at the top of the survey point is produced by the horizontal displacement of the survey point combined with its rotation. However, considering the type and installation conditions of these survey points, the rotation should be considered minimal. [A survey point is composed of a 7–8-ft (2.1–2.4-m) steel pipe, 8–10 in. (200–300 mm) in diameter, filled with concrete and embedded 4–5 ft (1.20–1.50 m) in the ground with a 30-in. (750-mm) diameter concrete block.] The main cause of this behavior should be attributed to the submergence of the upstream shell, which translates in increased settlement and the tendency of the upstream edge of the crest to bend towards upstream. The deflection towards downstream induced by the reservoir's water load is consequently diminished.

Conclusions

The study of 15 rockfill structures built by Hydro-Québec after 1950 has led to the following conclusions:

1. The deformation of these rockfill structures continued for a long time after the end of construction. However, considering that an annual rate of settlement below 0.02% *H* can practically be neglected, deformation can be considered complete 24–30 months following the end of construction.
2. The crest settlement of compacted rockfill dams (central or slightly inclined core) remains less than 0.35%.
3. The settlement of the rockfill on the downstream shoulders can reach 0.7–0.8% *H* following placement.
4. The maximum settlement (expressed as a percentage of height) does not always coincide with either the maximum recorded settlement value or the maximum thickness of the fill. The development of an arching phenomenon for relatively narrow valleys should be taken into consideration.
5. The influence of sluicing and lack of compaction is not obvious. The Bersimis and Desroches dams, where the rockfill was sluiced and placed by dumping only, show quite different deformations. At Bersimis the dam crest exhibits a settlement of 0.55% *H* after 320 months, while at Desroches it reaches 0.31% *H* for the same period, which is very close to that predicted for compacted rockfill dams. Even the probability of an arching phenomenon, detected slightly at Desroches dams (Fig. 18), cannot fully explain this difference.
6. The downstream deflection of the crest is equal to or greater than the settlement (with the exception of Bersimis 1 and Desroches dams), contrary to the conclusion of Lawton and Lester (2) and Clements (1).
7. Both the settlement and the downstream deflection of the dams and dikes (except at Bersimis) should remain inside the envelope curves in Figs. 19 and 20. Thus, these envelope curves could constitute a prediction method to evaluate future normal deformations of rockfill dams built on rock foundation. They can also be used as a quick guide to the future behavior of these structures: measured values falling inside the envelopes illustrate a normal and safe behavior. However, more precise

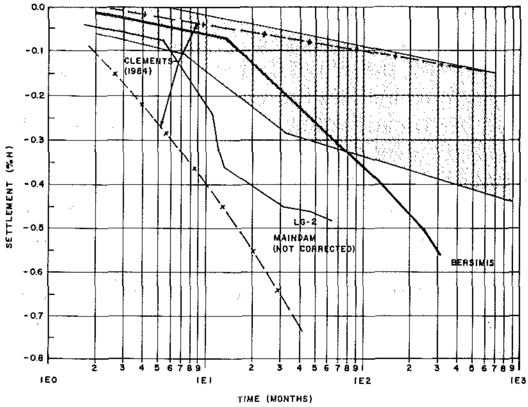

FIG. 19.—Settlement Envelope Curves for Analyzed Dams

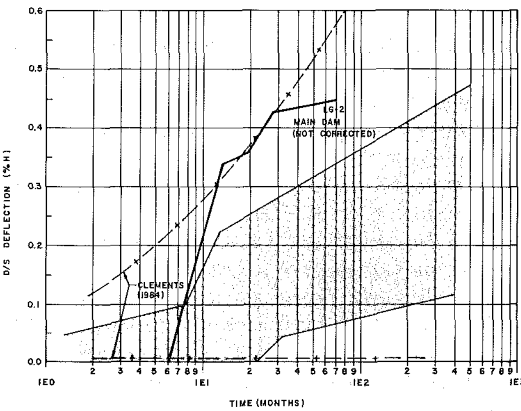

FIG. 20.—Deflection Envelope Curves for Analyzed Dams

monitoring and a more detailed analysis of the data are required when the measured values are outside these envelopes.

Acknowledgments

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Appendix.—References

1. Clements, R. P., "Post-Construction Deformation of Rockfill Dams," *Journal of Geotechnical Engineering*, ASCE, Vol. 110, No. 7, July, 1984, pp. 821–840.
2. Lawton, F. L., and Lester, M. D., "Settlement of Rockfill Dams," *Proceedings*, Eighth International Congress on Large Dams, Vol. III, Q.32 R.2, Edinburgh, Scotland, 1964.

3. Masseira, M., "Barrage principal LG-2—Rapport sur les fissures en crête du barrage," ("LG-2 Main Dam—Report Crest Fissures"), Société d'énergie de la Baie-James; Internal Report, Montreal, Canada, May, 1980.
4. Paré, J. J., "Earth Dam Behaviour on the La Grande Project," *Proceedings*, International Conference on Safety of Dams, Coimbra, Portugal, Apr., 1984.
5. Patterson, F. W., and MacDonald, D. H., "Rockfill Dams—The Bersimis Sloping-Core Dams," *Journal of Power Division*, ASCE, Vol. 84, No. PO4, Aug., 1958, pp. 1740–1741.
6. Penman, A. D. M. L., "Rockfill," *CP 15/71*, Build. Research Establishment, Watford, England, Apr., 1971, pp. 6–8.
7. Sowers, G. F., Williams, R. C., and Wallace, T. S., "Compressibility of Broken Rock and the Settlement of Rockfill," *Proceedings*, Sixth International Conference on Soil Mechanics and Foundation Engineering, Vol. II, Montreal, Canada, 1965.
8. Soydemir, C., and Kjaernsli, B., "Deformation of Membrane-Faced Rockfill Dams with Unyielding Foundations in Relation to the Design of Storvass Dam," *Report 53203*, Norwegian Geotechnical Institute, Oslo, Norway, Nov., 1975.

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