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Toulnustouc CFRD instrumentation overview and monitoring alternatives for future constructions

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ABSTRACT

Conventional instrumentation is utilized to monitor the behaviour of the Toulnustouc concrete face rockfill dam and dyke, as well as to confirm finite element model. Along with survey measurements, infiltration flow measurement weirs and strong motion accelerometers, each structure contained two cross sections of tiltmeters located in the central zone allowing measurement of face slab deflections, and joint movement detectors mostly located on left and right banks in tensile zones. The main objective of this paper is to present observations and relevant considerations in the use of such instrumentation for future CFRD constructions. Emerging technologies have become available since this project. An overview of new monitoring schemes which can be deployed as alternatives or redundancies and for measuring fill deformation parameters will also be exposed during this presentation.

Keywords: Concrete-face slab monitoring, Tiltmeter, Jointmeter, Fiber-Optic deformation sensor, MEMS inclinometer system, Robotic laser station.

1. INTRODUCTION

The Toulnustouc hydroelectric project is located in the North-East of the province of Quebec, Canada. The complex owned by Hydro-Quebec includes a 77m & 46m high Concrete Face Rockfill Dam (CFRD) and dyke, a spillway, a 9.8km headrace tunnel, an intake structure and a 526MW powerhouse.

In the earliest stages of the project design, consulting firm RSW Inc contacted Roctest for selecting appropriate geotechnical and structural instruments for monitoring the performance and behaviour of the CFRD structures. At first, an inclinometer system and settlement cells were discussed. However, the inclinometer solution, at that time, was deemed impracticable given the 37.5 degree slope of the concrete face of the dam and South dike. The use of soil settlement cells was also rejected because hydraulic tubing could be damaged by the coarse aggregates.

Along with survey monuments and V-notch weir for infiltration flow measurement, tiltmeters and jointmeters were chosen to monitor displacement on the upstream faces as dominant hydrostatic load moves the concrete face gradually in the downstream direction.

Conceptual information concerning the CFRD dam and South dyke is presented in an article published during the CDA 2006 conference (Beauséjour and al. 2006).

2. CRFD INSTRUMENTATION

2.1. Layout

Comprehensive 3-D Finite Element (FE) analysis study conducted by RSW Inc (Bouzaiène and al. 2006) to model stresses of the upstream concrete face slabs dictated the joint movement detector and tiltmeter locations as shown in the figure 1. Similar instrumentation layout was applied on the South dyke.

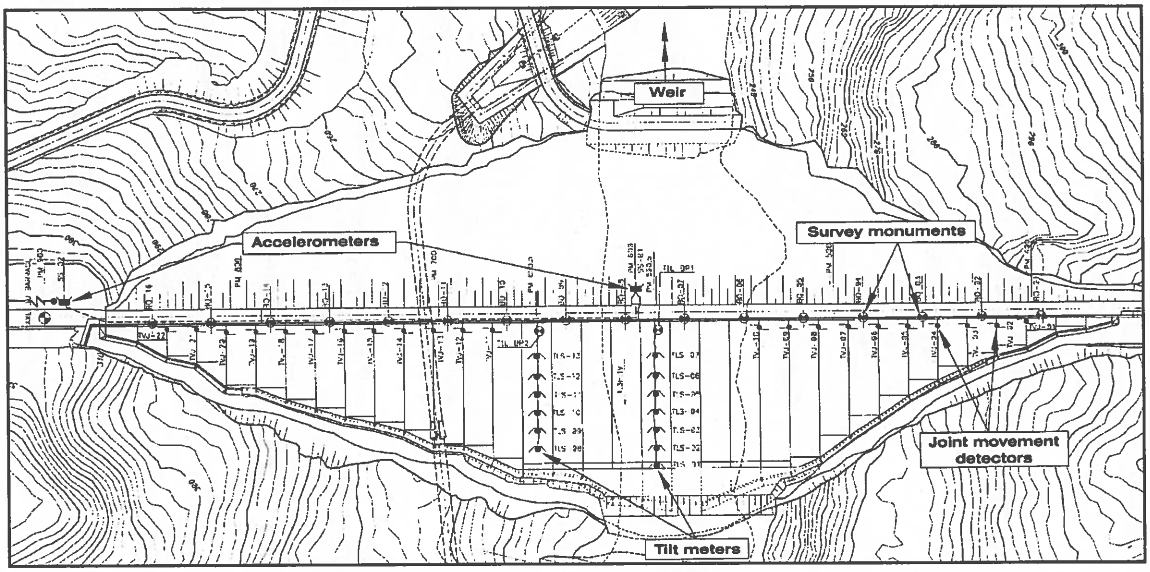


Figure 1 Main dam instrumentation plan view

2.2. Tiltmeter characteristics

Electrolytic tiltmeters sense angular movement using transducers and electronic signal conditioning. They can be described as very precise electronic spirit levels. They operate on the principle that a bubble, suspended in a liquid-filled case, tends to remain stationary with respect to the vertical gravity vector. As the instrument tilts, the case moves around the bubble. Platinum electrodes sense changes of resistance as they are alternatively covered or uncovered by the conductive liquid. Highly stable circuitry inside the tiltmeter body converts these changes to high-level voltage signals linearly proportional to angular rotation.

The model offered at Toulnustouc measures angular movements within a range of ±3 degrees with a resolution of 0.0006 degree (10.5 μradians) and repeatability of 0.001 degree. A special 6mm thick stainless steel enclosure with marine cable connectors completed the enclosure to meet harsh environment requirements.

2.2.1. Quality control and quality assurance QC/QA

In general, weather in Quebec can be very hostile with ambient temperature down to -40°C in winter and up to +35°C during summer. Rugged enough to resist these severe weather conditions (especially before the reservoir is filled), tiltmeters also need to withstand a maximum of 75m head of water.

After a factory calibration to confirm the temperature coefficient, waterproofing, and tilt calibration, each unit was subjected to rigorous temperature and pressure cycles for reproducing conditions to which the instruments would be exposed before, during, and after reservoir impoundment.

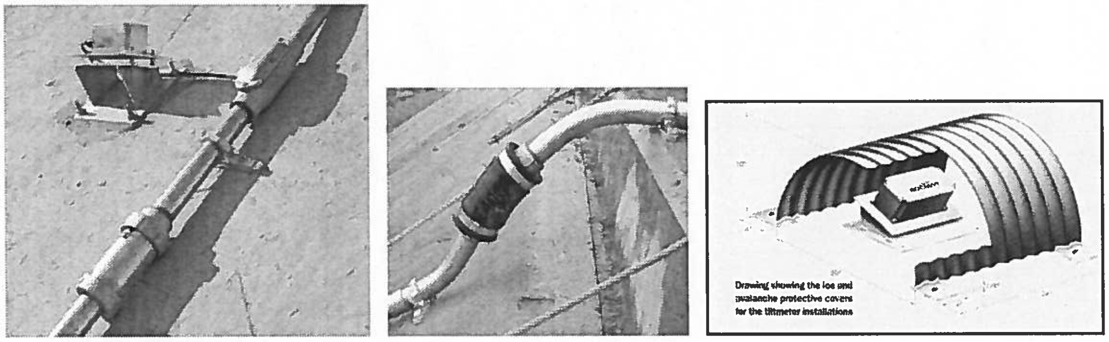
2.2.2. Installation details

Twenty four tiltmeters were utilised to monitor the deflection profile of the upstream concrete face slabs. Prior to the installation, all tiltmeter locations were surveyed (topography) and marked to assure accurate position along each section axis. Maximum deviation from the predefined axis was +/- 0.2 degrees. The concrete surface was smoothed out to remove any construction imperfections.

The tiltmeters were mounted on a stainless steel support adjusted to the slab inclination. A thick coat of Sika Grout or similar material was applied between the stainless steel supports and the concrete surface. This procedure helped to secure the support base to the slab and assured full contact. The stainless steel supports were anchored to the slab using 12 mm by 110 mm HVU Adhesive Capsule Anchor System with stainless steel anchors. Tiltmeters were then mounted on and zero adjustment was made.

The tiltmeter cables were protected with galvanized steel conduits (CSA-022.2) and secured to the slab using galvanized conduit clips and 9.5 mm Hilti anchors. Expansion joints were installed every 30 meters on the conduit with the addition of a universal joint at the junction between the slab and the dam crest parapet wall.

Cable manifolds from each cross-section were extended to terminal switching boxes located at the crest of the structures. Each terminal switching box has over-voltage protection and proper grounding hardware.



Drawing showing the ice and avalanche protective covers for the tiltmeter installations

Figure 2 Typical tiltmeter and protective cable conduit installation

Special galvanised steel covers were later fitted over each tiltmeter for additional protection, after ice accumulation and small avalanches damaged connectors during January-February 2005. The few damaged tiltmeters were brought back to Roctest's facility and were repaired, subjected to the same testing regimen, and reinstalled.

2.3. Jointmeter characteristics

The portable jointmeter consists of a stainless steel tube with a fixed conical seat at one end, and a spring-loaded conical seat, attached to a dial indicator at the other end. The measuring range of the dial gage is 0-50mm with an accuracy of 0.05mm and a resolution of 0.01mm.

The measurement is conducted by placing the instrument over two 25mm stainless steel reference balls anchored on each side of the joint.

2.3.1. Installation details

A total of 42 stainless steel reference anchor balls were installed at the junction of the crest/slab. Ribbed stainless steel anchors of 19mm diameter x 200mm long were installed on each side of a joint with an initial design span of 250mm. However, very tight structural reinforcement rebar grids did not allow standard anchor width installation with the result of creating numerous spans between anchors and requiring various extension tubes for the portable instrument.

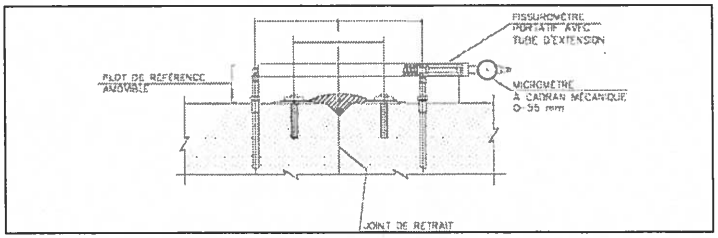


Figure 3 Joint movement detector details

3. DATA EXAMPLES

Tiltmeter and jointmeter data examples from the dam are shown in figures 4 and 5.

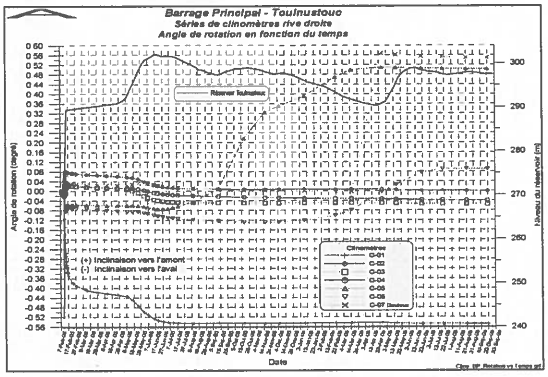


Figure 4 Tiltmeter plots – Main Dam

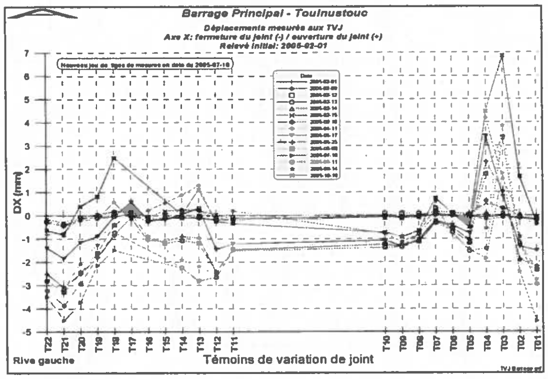


Figure 5 Jointmeter plots – Main Dam

4. OBSERVATION AND COMMENTS

Monitoring data indicates that 80% of the submersible tiltmeters are performing to specification. The remaining are presenting unusual results which, to date, have not been elucidated. A possible explanation would be that ice formation during winter construction or floating ice-blocks during reservoir filling may have misaligned the instruments. Damaged or altered wiring or shielding at the switching boxes may also be a potential cause of erratic readings. Decreasing the intervals between readings to weekly, daily or hourly readings through automatic data acquisition system (ADAS), had it been available, may have helped to further isolate the problem, eliminating human reading errors, permitting readings to be obtained in adverse weather 24 hours per day, improving accuracy, and generating an immediate warning when excessive movements occur.

Finally, tiltmeter cross-sections with more tiltmeters reducing the span between each instrument would have improved interpretation of the results. Of course, redundancy with other measurement means could be envisioned to better understand behaviour of the concrete-face slabs.

As for the jointmeter, installation of sleeves prior to concrete pouring would have, without a doubt, facilitated the installation of the reference anchor balls with a standard span as specified. To avoid temperature effect, reference anchor balls could have been located near the parapet away from the joints. Undoubtedly, a permanent installation with electrical jointmeters is most suited for such measurements which can allow automatic readings with ADAS as well as increasing safety of the personnel.

In this project, 3-D plinth/concrete face joint movement monitoring was not conducted. However, electrical jointmeters (three dimensional configurations) could have been utilized, especially where prominent tensile stresses have been identified (plinth alignment changes).

5. NEW ALTERNATIVES

Emerging technologies have become available since this project. Overviews of new monitoring schemes which can be deployed as alternatives or redundancies are presented in the following paragraphs.

5.1. Fiber Sensing

Optical fiber monitoring instruments to measure structural deformation has now become a well-known technique in the civil engineering industry. As shown in figure 6, the underlying concept is to use a long-gauge fiber-optic sensor to measure differential strain variation between two parallel planes, in this case the top and bottom reinforcement rebar layers, in order to determine slab deformations and displacements (deflection).

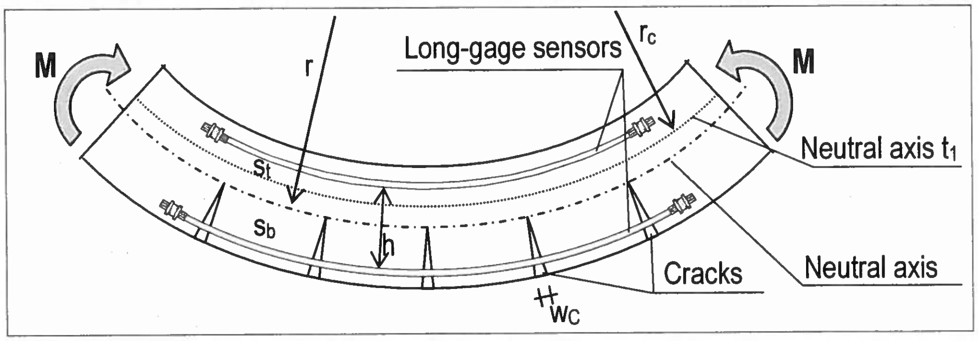


Figure 6 Optical fiber installations in the concrete-face slab.

Working under the Michelson Interferometer or Fiber Bragg Grating (FBGs) principles, a chain (multiplexed) of several sensors, can be deployed and affixed one after another, prior to concrete pouring, to the defined rebar cross-section allowing strain measurements at several locations. Similar concept is applicable with distributed strain sensing based on the Brillouin scattering principle providing local strain measurements (every 0.5m) at thousands of locations by means of one single optical fiber sensor over several tens of kilometres, if needed. The table below shows typical characteristics of the three technologies which are currently available in the industry.

Specifically packaged for rough and harsh environment, fiber-optic sensors as offered by Smartec SA (Member of Roctest Group) allow easy and rapid installation using tie-wraps or hose clamps to affix the sensor to the reinforcement rebar.

Sensor Type	Sensor Base	Elongation	Resolution/Accuracy
Long base (Michelson)	10m	1%	2 μm over gage length
Multiplexed (FBGs)	2m	0.75%	0.2 με / 2 με
Distributed (Brillouin scattering)	250 km	1.5% (locally)	2 με / 20 με

The two strain gauges parallel to the neutral axis, separated by a distance **h,** allow the calculation of **K,** the curvature as express in equation 1. The first integration (2) of **K** gives rotations and a second integration (3) provides the displacements.

$$\frac{\varepsilon_1 - \varepsilon_2}{h} = \frac{1}{r} = K \qquad (1)$$

Where, ε is the strain
r the radius of curvature

$$u' = \int K(x)dx \qquad (2)$$

$$u = \int u'dx = \iint u''d^2x \qquad (3)$$

Evidently, two boundary conditions are necessary to define completely the displacements, such as a rotation at one point, displacement continuity or a known displacement at one point. This information can be obtained by Tiltmeter measurements and surveying campaigns.

Spatial displacement obtained from these measures needs appropriate mathematic algorithm and interpretation software which are also commercially available.

5.2. MEMS Inclinometer System

The use of an inclinometer system for deflection profiling is a fairly old concept. However, force balance accelerometers integrated for few decades did not allow measurements beyond ± 30 degrees from vertical with a system accuracy of 2mm over 25m. The forthcoming of Micro-Electro-Mechanical Systems (MEMS) by the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro-fabrication technology brought the inclinometer measurements to a higher level.

Completely redesigned to incorporate modern technology and materials, the micro-controller offers a variety of measuring angle ranges to equivalent CFRD slope designs with the same system accuracy. Manual readings through wireless communication can be taken from the PDA as the probe is incrementally hoisted. An alternative would also be a series of in-place inclinometer sensors, working under the same technology, installed at preset intervals in the inclinometer casing for permanent and remote monitoring with an ADAS.

For new construction or during rehabilitation of existing CFRD, the ABS inclinometer casing could be installed on the upstream concrete face. To minimize practical issues, similar installation procedures as mentioned in the tiltmeter section should be considered.

To avoid any difficulties, the ABS casing should preferably be embedded in the extruded curbs between the upstream face and the material fill providing no interference during the construction of the concrete-face slabs. Furthermore, casing installation under the slabs would not deteriorate its integrity.

5.3. Robotic laser movement detection

Robotic Laser Station (RLS) is a survey instrument combining a laser distance meter and a bi-axial modular robotization with automatic target recognition. The instrument is able to monitor continuously a large number of points in 3D space by sighting targets, e.g. prisms, and following them as movements occur. Properly configured to operate at different intervals, the RLS searches other prisms localized within the construction zone of influence. Using stable reference targets arrangement (triangulation), the instrument processes the signals and post analysis is achieved with the control software.

Undoubtedly, monitoring points on the crest and downstream face is usually the first choice for long-term measurements of surface settlement. Measurements are normally made by optical or trigonometric levelling, but accurate and reliable robotic laser stations are likely to be used with increasing frequency in the future as they became very affordable and easy to install.

The early deployment of this instrument with prisms on the concrete-face slabs, during its construction phase, would be beneficial to engineers for evaluating vertical modulus of elasticity, and of course, estimating the maximum concrete slab displacement.

Measurable distance with today's lasers, like the Robovec model, can reach up to 0.7 to 1 kilometre with an accuracy of ±1 mm as the instrument performs a pre-defined number of laser shots and statistically analyse the resulting measurements. Standard deviation for outdoor measurements is 1-3mm during the day and <1mm at night.

6. CONCLUSION

The following conclusions can be drawn from the Toulnustouc CFRD concrete face slabs monitoring:

- Tiltmeters are good instruments for slab displacement monitoring. However, like any surface instruments, special care should be taken for protecting the instruments and related accessories properly.
- Decreasing the intervals between readings to weekly, daily or hourly readings through ADAS may have helped to better understand erratic behaviour of certain tiltmeters. Continuous monitoring would have enabled to observe rates of movement and correlate concrete face slab behaviour with external factors and seasonal trends during construction. Of course, the use of ADAS should not be to the detriment of visual observation. Manual readings checks should always be part of the monitoring program.

- For safety issues, the use of mechanical joint movement detection is undeniably not the most adequate device for joint opening measurements in CFRD application. A more viable solution would be surface extensometers with linear displacement transducers which will allow manual data collection from a secure location and the possibility of continuous monitoring, if needed.
- Redundancy with other measurement means such as optical fiber sensing, inclined inclinometer system or Robotic Laser Stations is strongly encouraged and recommended for increasing monitoring success.

7. ACKNOWLEDGMENT

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