Introduction

Hydro-Quebec (HQ) is an integrated state-owned electricity company which builds and operates dams, generating power plants, transmission lines and distribution networks in the province of Quebec, Canada. Its total installed capacity reaches more than 40,000 MW from which hydro power represents over 90%. Its sales, domestic and international (to USA and neighbouring provinces of Canada), is in the order of 10 billion $ annually.

In the last half century, HQ has built almost 500 dams and dykes in various soil and rock foundation and throughout the time, it has got valuable experiences on foundation treatment, either on new or on existing structures:

- The most reputed and well-known case is the cut-off walls of Manic-3 main dam built in 1971-72
- This project is followed in the 80's and 90's with the development of the James Bay Complex, where others modern soil foundation treatments were in application, and mostly at:
  - CH-20 dam of LG-2 powerplant
  - OA-11 dam of the EOL reservoir
  - South dykes of the LG-3 powerplant
- And presently with the on-going Peribonka hydropower development in 2005

Basic Philosophy and Approach

The well-known expert Pr. Harry R. Cedergren has stated out one time that engineering works involving water, in our case dams and dykes, can usually be made safe by:

- Keeping the water out of the places where it can cause harm, by using watertight barriers like cut-off trenches, impervious membranes or blankets and grout curtains, or:
- Controlling by drainage methods, by using filters and drains, relief wells, etc.

In most cases, combinations of these two fundamental methods are used successfully to control ground water, seepage avoiding instability and failure by piping, internal erosion, etc.
HQ approach regarding the foundation treatment, by all these times, does not deviate from this sage philosophy.

Hydro Quebec past experiences

1. **Manic 3: cut-off walls**

   The most reputed and well-known case is the cut-off walls of Manic-3 main dam built in 1971-72
   
   ◆ The 107 m high earth dam, commissioned in 1975, is built on a 126 m of alluvial deposits.
   
   ◆ The presence of a pervious granular and compressible foundation (loose sand) required special techniques to reduce seepage through foundation, and to avoid cracking of the till core caused by differential settlement of the foundation (bentonite cap).
   
   ◆ A positive double cutoff walls was constructed, and consisting of 2 rows of 3m apart of cast-in-place 0,6m thick interlocking piles and panels, anchored 0,6 m minimum in bedrock and topped by an inspection tunnel, and completed with grout curtain.
   
   ◆ The interlocking piles were constructed by drilling 0,6m diameter circular “primary” piles at 1,2 m centers, followed by biconcave “secondary” piles.
   
   ◆ From then, the cutoff walls continue to perform well until now.

---

**MANIC-3 – Canyon Cross-section**

![Diagram of Manic-3 Canyon Cross-section](image-url)
2. **LG-2 Hydropower project : CH-20 Dam**

- The CH-20 Dam (6 052m long, 51.8m max height) is a very special case illustrating many foundation treatments to accommodate variability of soils, varying from near surface bedrock to deep alluvium deposits, with sand & gravel and silty sand.

- To optimize foundation treatments for an efficient seepage control, specific design is based on:

  Core or key trench anchored into bedrock, where overburden soils can be excavated safely.

  - Where bedrock is too deep to be reached by backhoe excavation, specific foundation treatments must be adopted:
- Positive cutoffs with slurry trench or cutoff wall.
- Impervious upstream blanket and downstream relief wells

CH-20 Dam – Overview

CH-20 Dam: Highlights

CH-20 Dam – Plan view
CH-20 Dam: Foundation treatments

Where the thickness of overburden is very important, an efficient seepage control throughout the foundations can be made, using:

- An **impervious upstream blanket** (L=7H) built with till material to lengthen the seepage path and aiming to reduce the upward...
exit gradient at the down-stream toe. At CH-20 Dam, the effectiveness of this approach is improved with the presence of 14 relief wells (20m depth and 20 m of distance)

- A slurry trench, built under the till core and filled with impervious materials (sand, till and bentonite) to make a watertight barrier. At CH-20 Dam, 24 relief wells were added in this area for a better control of exit gradient at the downstream toe.

- A concrete panel wall as a positive cutoff.

CH-20 Dam – Upstream blanket Section

CH-20 Dam – Slurry Trench Section

CH-20 Dam – Concrete cutoff wall Section
CH-20 Dam: Comparative performance

- Based on piezometric and relief discharge values as measured in downstream, the effectiveness of different foundation treatments at CH-20 Dam can be resumed as follow:
  - Based on head loss at downstream toe:
    If the section of impervious blanket is taken as reference, the average head loss at the concrete cutoff section is 22 m, as compared with a head loss varying between 4 to 15 m at the Slurry trench section.
  - Based on exit gradient at downstream toe:
    Impervious blanket section: gradient between 0.36 to 0.90.
    - Slurry trench section: average gradient around 0.5, with upper bound near the critical gradient of 0.85 to 1.1.
    - Concrete cutoff wall section: exit gradient is 0.23.
- Without no doubt, concrete cutoff wall is the most efficient measure for seepage control.
- Relief wells lost most of their efficiency over the time.

CH-20 Dam – Slurry Trench Performance
3. **OA-11 Dam and EOL Reservoir**

**OA-11 Dam of the EOL Reservoir**
This 3.2 Km long et 33m height dam is founded on an important alluvium and till deposits, with different foundation treatments, from right to left:

- **Slurry trench sections**, anchored mostly into impervious till, and rarely into bedrock. These sections covered mostly 65% of the dam.

- **Central key trench**, anchored into impervious till underneath. This section is served as transition from slurry trench to concrete panel wall cutoff.

- **Concrete cutoff wall**: the cutoff wall is anchored into bedrock. Panels were excavated using the "Kelly Bar" technique, and not with hydraulic clamshells.

To consolidate some riverbed sections, mostly below the downstream cofferdam, the technique of vibro-compaction was required.
OA-11 Dam – Slurry Trench Section

OA-11 Dam – Key Trench into Impervious Till
OA-11 Dam: Comparative performance

◆ Slurry trench sections:

Many execution problems have been encountered during construction.

The overall performance of the slurry trench is below the expected design level. Many "windows" are suspected throughout or below the slurry trench.

Downstream weighted and filtered berms are required to ensure stability. Closed monitoring and surveillance are required, when reservoir is at high level.

OA-11 Dam – Slurry Trench - Seepage
OA-11 Dam – Key trench - Seepage Analysis

Key trench section: Some high piezometric levels and downstream exit gradient are observed. But overall stability is checked.

Concrete cutoff wall: The overall performance is satisfying.

4. LG-3 Hydropower project, South Dykes

This case study presents a particular aspect: the sophisticated foundation treatments for South Dykes (TA-27C to TA-32 A&B) were not expected in the initial design like the previous cases.

These treatments were required during the first reservoir impounding in 1982, when reservoir were 3 m below the maximum water level.

Important leakages from the foundations, very high piezometric level at downstream toe, exit gradient quite high (i > 0,5 @ 0,7), and finally many important landslides on the reservoir rim or in downstream areas. These unsecured phenomena were conducted to the stabilizing works as realized in 1983.

These dykes are now performing quite well.

South Dykes: Stabilizing Works

For Dykes TA-27C to TA-32 A & B, stabilizing works as done can be resumed as follow:
LG-3 Main Dam

- **Slurry trenches**: they were mostly executed along the reservoir rim, and where bedrock are not too deep to be reached by open excavation with backhoes.

- **Concrete cutoff walls**: these cutoffs were built on the crest or on the upstream blanket of existing dykes.

**Cement grouting**: Upstream of Dyke TA-27C, the projected slurry trench can not be done because presence of very important large blocks, and was replaced by a large campaign of cement grouting. But the final results were quite poor.

- For Dyke TA-26B, no positive cutoff can be done (bedrock is too deep), and its overall stability is assumed only by drainage: U/S blanket (L=22 H), D/S filtered berm, relief wells, drainage ditches, etc…
LG-3 Project - Dyke TA-26 B (Downstream)

◆ For concrete wall cutoffs as realized in 1983, some field data and basic information are as follow:
  ■ **Cutoff wall**: interlocking panels, 0.6m width, 6 to 8 m long, and max 60 m depth.
  ■ **Concrete** with E/C =0,5 and 20 MPa compression.
  ■ **Slurry**: plastic viscosity at 11 to 16 centipoises, or 44 to 60 seconds Marsh.
  ■ **Excavation**: with hydraulic clamshells and backhoes.
  **Anchored** 0.5 m min into bedrock, obtained with important chiseling (trepans 8-10 T) operations.
  ■ **Verticality**: deviation less than 1/400, max 15 cm.

Main field problems: control of mud losses through very pervious strata; stability of the excavation walls; anchor into bedrock; "windows" problems, etc...

5. **Ste-Anne Lake, Southeast Dyke**
Ste-Anne Lake, S-E Dyke – U/S View

Ste-Anne Lake, S-E Dyke – D/S View
Like the TA-26B Dyke at LG-3 Hydropower project, no positive cutoff can be physically done at the Ste S-E Dyke, throughout the important alluvium of more than 200m depth, filled with coarse sand, gravels and cobbles.

The safety of S-E Dyke of Lac St-Anne is entirely assumed by different drainage systems:

- An upstream impervious blanket covered mostly all of water entrance, and is lengthened in 2002.
  - A large and filtered stabilizing berm on the down-stream terrace, upgraded recently.
  - Series of 7 existing relief wells.

Many temptations were made in the past to grout the overburden soils and aiming to control the water seepage and exit gradient at downstream toe, with no conclusive results.

- To monitor the safety performance of this dyke, an extensive monitoring program was built and upgraded with time:
- A network of more than 40 hydraulic and electrical piezometers to monitor pressure build-up in the foundations, and to evaluate exit gradient.

**Ste-Anne Lake, S-E Dyke Performance**

**Ste-Anne Lake, S-E Dyke – Instrumentation Plan**

- 2 Parshall weirs to monitor total seepage discharge.
- Mini-propeller to monitor seepage profile for relief wells.
- Total seepage at full head before remedial works: more than 500 l/sec.
- After the remedial works in 2002:
  - Total seepage at full head: 380 l/sec.
  - Exit gradient at D/S toe: 0.24 to 0.33.
  - Safety factor against uplift: 1.5 to 1.7.

**Current challenge**

**Peribonka Hydropower Development: Highlights**

Peribonka is actually one of several hydro projects under construction by HQ. Peribonka dam and power station are located in northern Quebec, around 600 km from Montreal. The project consists mainly of a 83m high dam (773m length), and an underground power house and a diversion tunnel located on the left bank. The spillway is located and excavated on the right bank.

The dam is a zoned rock fill embankment with a central core composed of glacial till. SNC-Lavalin, a Montreal Consulting firm, is the designer, and HQ the owner. One of the main concerns in Peribonka is the dam foundation in the river channel. It is in fact, a 125m deep gorge filled with fine (occasionally loose) sand in the upper part (30m depth) and an important coarse and
pervious material (cobbles, known as Cocos zone) in the lower part. Other sensitive and key element is the foundation treatment schedule which must fit in a short period of 15 months.

To ensure seepage and uplift control and the overall stability of the structure, a cut-off wall of around 8200 sq.m, under the central core is needed. Cut-off of this nature implies many technical and practical concerns which must be resolved and overcame by all partners: owner, designer, contractor.

Peribonka Main Dam – Plan view

Peribonka Main Dam – Longitudinal section
For the Main Dam, a deep cutoff of 125 m depth is required to control seepage throughout pervious foundations, and to ensure the overall safety and stability of the structure.

The cutoff will be made with plastic concrete of 3 MPa in compression, from a mixture of cement-bentonite (20%). This concrete will be non-erosive.

The compaction of the riverbed section, in a loose sand strata, is required beforehand. It can be achieved by vibro-compaction technics.

All modern foundation treatments are required to build the cutoff panels at the deep gorge section, filled with coarse materials and cobbles (K=1cm/s).

But a very short schedule (15 months) is the key and critical element of this project.

Peribonka : Technical challenges

During the design period in 2004, many technical problems have been analysed and overcomed :

- **Choice of concrete** : plastic concrete is finally selected due to its propensity to accommodate large deformations and its strain compatibility with surrounding soils. But potential erosion remains a long-term concern.

- **Densification of platform** : With available vibro-compaction technics, a relative density of 70% is required in loose sand formation, at 30 m depth.

- **Grouting in alluvium soils** : To avoid mud losses in coarse and pervious soils at the deep gorge, an important grouting campaign must be done before-hand. It can be achieved with
"tube-à-manchette" technics, and cement grouting must diminish average permeability, from 1 cm/s to mostly $10^{-2}$ cm/s.

◆ Major technical challenges:

- **Panels excavation**: It can be done with clamshell and hydrofraise combination. The control of stability of the excavation walls, risks of mud losses, and the deviation of verticality (< 1/100) constitute main concerns at this phase.

- **Steep slopes and "Windows"**: At the vicinity of deep gorge section, initial design foresaw that "windows" below the panels can be let in place, and to be treated after the completion of the cutoff by cement or jet-grouting through boreholes. This design is finally rejected, because:
  
  a) Grouting can not assure the same performance as with the cutoff ($10^{-4}$ cm/s vs $10^{-6}$ cm/s as requested).
  
  b) Risk of concentrated flows through "windows" is high, and can make the cutoff less efficient, with exit gradient at the downstream toe of the dam too high.

- **Bedrock anchoring**: Excavation of rock will be very difficult near steep slopes of the deep gorge, but it is feasible with special "hydrofraise" bits. It is cost effective vs special treatments of "windows", and will have no impact on the overall schedule. By the way, full anchoring of the wall into bedrock is the best way to ensure the imperviousness of the cutoff.

- **Grouting limits**: Based on contractor bids, soils grouting will reach these practical limits:
  
  - Cement grouting: permeability obtained will be greater than $10^{-4}$ cm/s, even under favorable conditions.
  
  - Microfine cement grouting: K will be in the order of $10^{-4}$ to $10^{-5}$ cm/s.
  
  - Chemical grouting: Very expensive method, but it must be required if permeability of $10^{-6}$ cm/s is required.
In spite of these preparations, it is believed that the real challenge and lesson will be drawn throughout the construction and the subsequent periods of impounding, monitoring, surveillance, etc.

**Hydrofraise System**

**Hydrofraise Bits**
Excavation of "Primary" Pane

Windows and Bedrock Anchoring
Typical Schedule Projected

Conclusion

In term of dam foundation treatments:

1. It is believed that suitable and adapted measures to the foundation nature and condition and to the current practices are keys for success

2. Therefore, well knowledge of these fundamental elements is essential prior to any action or decision.

3. Accurate and extensive monitoring, surveillance and observation during and after construction are the best master.

4. Adjusting measures afterward are seen as a normal and necessary process and not as a half success or a half failure result.