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NIAGARA TUNNEL

Hatch Mott MacDonald

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Niagara Tunnel

Client: Ontario Power Generation

Project Description:

The Niagara Tunnel is the largest hydroelectric project in Ontario in 50 years and will provide renewable power over the next 100 years. The tunnel is 10.2 km long, with a bored diameter of 14.44 m (the height of a four-storey building). At its deepest point, it is 140 m below the city of Niagara Falls, Ontario. Put into service on March 9, 2013, it can carry 500 m^3/second of water from the Niagara River above Horseshoe Falls to the existing Ontario Power Generation's generating facilities downstream at Queenston.

As Owner's Representative, Hatch Mott MacDonald (HMM) and Hatch developed the concept design and set out the Owner's mandatory requirements to ensure a 90-year service life without any outages. HMM and Hatch assisted OPG with the international request for proposal, and then interviewed and scored prospective contractors.

After selecting a two-pass design/build method, HMM/Hatch administered the contract, audited the contractor's detail design, quality and safety; and reviewed, critiqued, and, after required revisions, accepted its designs of mission critical systems. These involved several worldwide firsts: the largest hard rock TBM at the time; the largest pre-stressed non-reinforced 600 mm thick concrete liner; a full surface electrically testable polyolefin liner developed specifically for the project to protect the concrete liner from corrosive water in the host rock and to prevent the transfer of freshwater/chlorine ions to the rock (which was prone to swelling); the use of full-surface scanning (no targets) revolving lasers to measure concrete deflection in real time during high pressure (20 bar), pre-stress accurate to +/- 0.5 mm.

Project Objectives, Solutions and Achievements:

The Niagara River is an international waterway forming part of the boundary between Canada and the United States of America. The river is about 53 km long with an average flow of approximately 6,000 cubic metres per second (m^3/s).

The hydroelectric resource at Niagara is shared with the United States in accordance with the terms of the 1950 Niagara Diversion Treaty. This treaty established priority for scenic, domestic and navigational purposes and allows the remaining flow to be used for power generation. The scenic flow requirement is 2,832 m^3/s during the daytime from April through October, and 1,416 m^3/s at all other times. About two-thirds of the average Niagara River flow is available for power generation and is shared equally by Canada and the United States.

In the 1980s, Ontario Hydro, the predecessor to Ontario Power Generation (OPG), began exploring the possibility of developing more power at Niagara Falls' Sir Adam Beck (SAB) generating complex.

Hatch was involved from the onset of the preliminary engineering and the environmental assessment (EA) for the proposed Niagara River Hydroelectric Development (NRHD). The NRHD EA was approved by Ontario's Ministry of Environment in October 1998. The approved project included construction of two additional diversion tunnels and an underground generating station north of the existing SAB generating stations.

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Table 1. Diversion and Generation Capacities

	In-Service Year	Diversion Capacity (m^3/s)	Station Capacity (MW)	Annual Energy (GWh)
Sir Adam Beck 1	1922	625	487	2,700
Sir Adam Beck 2	1954	1,200	1,472	9,200
Sir Adam Beck PGS	1958	-	122	100
Previous Totals		1,825	2,081	11,800
Niagara Tunnel Project	2013	500	-	1,600
New Totals		2325	2,081	13,400

In July 2004, OPG decided to proceed with the Niagara Tunnel Project, a design/build initiative for one of the diversion tunnels. OPG selected the HMM/Hatch team to provide all Owner's Representative services for the project, including concept engineering, geotechnical investigations, preparation of the geotechnical baseline report and preparation of the technical and commercial documents for a competitive international proposal competition for the execution of the project.

The diversion tunnel is designed to divert a nominal 500 m^3/s of water to OPG's SAB Generating Station, allowing more efficient use of the Niagara River flow available to Canada for power generation, facilitating an increase in average annual energy output of about 1,500 GWh (13%). The second diversion tunnel and underground powerhouse could be constructed in the future, depending on energy requirements and project economics.

Before construction of the new tunnel, the flow in the Niagara River that was available to Canada for power generation varied from approximately 1000 m^3/s to 3000 m^3/s, exceeding the existing SAB diversion capacity (canal and two tunnels) about 65% of the time. With the availability of a nominal 500 m^3/s from the new diversion tunnel, the available flow will exceed SABs diversion capability only about 15% of the time.

Technical Excellence and Innovation:

The sheer size of the tunnel and the geological conditions along its route required several important innovations in design and construction techniques. The diversion tunnel was excavated using a two-pass tunnelling system. The 14.44 m diameter Robbins open-gripper tunnel boring machine (TBM), popularly known as 'Big Becky', was employed to excavate the tunnel. When it was commissioned, Big Becky was the largest hard-rock TBM in the world, standing at the height of a four-storey building and weighing 4,000 tonnes. The TBM excavated approximately 1.7 million m^3 of rock, which was transported through the tunnel by conveyor belt and stored on OPG property. The bored tunnel was initially supported by rock bolts, steel channels, steel mesh and shotcrete, the latter applied from the TBM trailers. The final lining consists of an impermeable membrane and a 600 mm thick unreinforced concrete liner that is pre-stressed with interface grout.

The following design criteria led to the adoption of the two-pass system and the choice of an unreinforced cast-in-place concrete liner:

1. The final liner needed to be completely watertight to prevent fresh water from entering the surrounding rock mass. A characteristic of the Queenston formation, through which the deepest section of the tunnel is constructed, is the potential of rock swelling in the presence of fresh water due to a migration of chloride ions from the chloride-rich pore water.
2. The ambient groundwater in the host rock formations is very corrosive, which led the designers to minimize the use of steel reinforcement in the final liner.
3. The tunnel needed to be as hydraulically efficient as possible to reduce head losses due to friction and to minimize the impact on incremental generation at the Sir Adam Beck hydro stations.

Taking these criteria into consideration and following a detailed constructability review, the Austrian design-build contractor adopted two novel concepts for the tunnel, (1) the use of a waterproof membrane, and (2) pre-stress grouting between the concrete liner and the rock after the concrete had gained its design strength.

The tunnel has a waterproof membrane between the initial and final lining that was fully testable in-place prior to pouring the concrete liner. The waterproofing membrane system combines a layered polyolefin membrane with a layer of geotextile fleece that provides protection from damage by contact with the shotcrete. The fleece is backed by a thin plastic membrane that facilitates flow of the interface grout. The outer layer of polyolefin and the fleece are conductive. By applying a high voltage (low amperage) potential across them, any flaw in the main membrane is exposed by an electrical short. The resultant singeing is visible and is recorded by heat cameras.

The interface between the inside of the membrane and the cast-in-place concrete lining was contact grouted over the full circumference of the tunnel. Low-pressure cement grout filled any voids and imperfections within the concrete lining. A second stage of interface grouting, with pressures of up to 20 bar, was carried out through a system of grout-hose rings installed at regular intervals between the initial shotcrete lining and the waterproofing membrane. Grout blocking rings were provided around the circumference to control the flow of grout along the tunnel during the high-pressure grouting operation. These details ensured uniform grout distribution through the geotextile fleece and facilitated the filling of joints and cracks in the initial lining and the surrounding rock. They also ensured compression of the concrete liner to offset the internal water pressure of up to 14 bar at the deepest section of the tunnel under operating conditions.

The success of the interface grouting was carefully monitored by precise deformation measurements of the full circumference of the tunnel. Fixed monitoring sections were surveyed before and after interface grouting. Up to four sections in each 12.5 m bay were measured by moving gantry-mounted laser scanners capable of detecting deformations to ± 0.5mm during the interface grouting process. Pumping pressures defined by structural analysis based on the as-built thickness and tested strength of each concrete bay were kept within the allowable limits and pressures were automatically controlled as threshold values were reached. Interface grouting was the final step in ensuring the 90-year design life of the tunnel as demanded by the contractual Owner's Mandatory Requirements set by HMM/Hatch.

The design-build team was required to submit all technical documentation relating to the design and construction of the work to HMM/Hatch for review, and the HMM/Hatch team carried out independent analyses of all the critical components of the work. The close working relationship between the designer, the constructor and the HMM/Hatch team fostered a cooperative approach to problem solving which led to real economies in cost and schedule.

Level of Complexity and Project Challenges :

Every aspect of the Niagara Tunnel Project included high levels of complexity and challenges that required adopting innovative solutions and close cooperation between the HMM/Hatch team, the design-build contractor, and all other stakeholders. Some examples are the contracting model adopted to complete the project, to the design and fabrication of the world's largest hard-rock TBM, to the intricate technical issues encountered when developing the electrically testable waterproof membrane, and the laser scanner measurement of deflection of the concrete liner to 0.5mm accuracy during high-pressure grouting.

Several requirements were attached to the approval of the environmental assessment that led to logistical issues that the project planners, designers and constructors had to overcome. The environmental assessment approval for the Niagara Tunnel Project ruled out excavation by blasting and locating access shafts within the city limits.

This led to two fundamental logistical aspects of the project, (1) the rock excavation would be done by a tunnel boring machine (TBM), and, (2) the excavation would be carried out from a single entry point heading from the outlet end to the intake end, a distance of 10.2 km. The size of the finished tunnel required the design and construction of a hard-rock TBM of greater diameter than any previously constructed.

This approach meant that all the underground work had to be accessed from a single entrance at the outlet end of the tunnel on property owned by OPG. In order to allow concurrent activities, all tunnel operational equipment had to be designed to allow traffic to pass to and from the TBM. To limit traffic in the tunnel, all rock removal was done using a conveyor that ran at the end of the excavation for approximately 11 km to the rock disposal site.

Concrete was supplied from an on-site batch plant and from a local concrete plant. Delivery to the separate invert and arch forms used a variety of methods, including pumping, drop shafts from the surface, and trucks operating in the tunnel. At times the concrete was pumped horizontally for 1.4 km, requiring very precise mix design and quality control of concrete production. At peak production, the two 12.5 m long invert and arch forms were continuously moved every 24 hours, 7 days a week for several months.

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The intake is located immediately below the International Control Structure in the upper Niagara River, upstream of Niagara Falls. It was recognized that excavating through the fractured rock layers below the river could present serious inflow problems for the TBM. An advanced grout tunnel was excavated by drill-and-blast through the first 300 m of the excavation from the intake portal and was pressure grouted to provide a solid dry passage for the TBM.

Contribution to Economic, Social and/or Environmental Quality of Life:

The Niagara Tunnel was built to deliver up to 500 m^3/sec of Niagara River water to existing generating facilities and produce 1.5 TWh per year of clean renewable energy for the people of Ontario for the next 100 years or more. That is enough energy to power a whole city the size of Kingston or Barrie in Ontario. It also ensures that that amount of additional load is not serviced by "dirty" providers or far more expensive ones.

During the construction of the facility, approximately $1 billion in economic benefit was generated in the Niagara Region.

The rock extracted during mining was stored on OPG property in a location with easy future access by third parties. The rock from the Queenston formation is available at no charge to the Ontario brick industry for reuse in brick making. One manufacturer of specialty bricks has been using this material for two years. This recycling has the potential to reduce the need for additional open-cast clay mining and to lower the price of house building materials. The remainder of the rock is available as earth fill for highway construction. The harder limestones encountered were crushed and graded for road construction. Over the years to come, this has the potential to be a 1.7 million m^3 recycling program.

Several features of the design and construction were chosen to have a minimal impact on the local environment and the critically important tourist industry of the region:

- In the 1950s, two water delivery tunnels were built by OPG on the same horizontal alignment as the new tunnel. They used the drill-and-blast method and were advanced in both directions from several shafts throughout the City of Niagara Falls. The excavated rock was extracted from these shafts and trucked on City and Regional roads to OPG's lands at the Sir Adam Beck Generating facilities. To prevent environmental impact (dust, carbon emissions, noise, bright lights, etc.), the new tunnel was bored from within the OPG lands and exited into a cofferdam in the Niagara River under Gate 1 of the International Niagara Control Works. All entry to and exit from the tunnel, all rock extraction and all concrete production and delivery took place on the secured OPG property 24/7, 364 days a year. (There was no work on December 5, Santa Barbara's Day, the patron saint of miners. On that day there was a non-dominational service inside the tunnel with a local choir. The acoustics were phenomenal!)

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- The new tunnel had to cross a sensitive buried geological feature called St. David's Gorge. It is essentially the gorge previously occupied by the Niagara River when it flowed straight through the current location of the whirlpool, where today it makes a 90° right turn. This gorge is filled with a mix of glacial and alluvial materials and contains a water table that feeds vineyards and other agricultural activities downstream in Niagara on the Lake. To avoid any impact, the tunnel alignment was designed as a syphon that passed under the gorge at a depth of 140 metres, notwithstanding that this added greatly to the logistical issues to be dealt with.

During construction, HMM and Hatch had to ensure strict control of Environmental and Safety supervision by the Contractor. The project waters are a source of drinking water for millions of people and wild life, and are fish habitat on both sides of the Canada/US border. The project was completed with ZERO impact on the water table and the lake and river water. Also, the incidence of lost-time injuries was HALF the provincial average and there were ZERO life-threatening injuries – remarkable statistics on a project of this magnitude. The stringent risk management system installed by HMM/Hatch proved to be extremely effective.

Placing arch concrete liner

Upstream cofferdam and ice deflection wall

Launching arch concrete forms in outlet cut

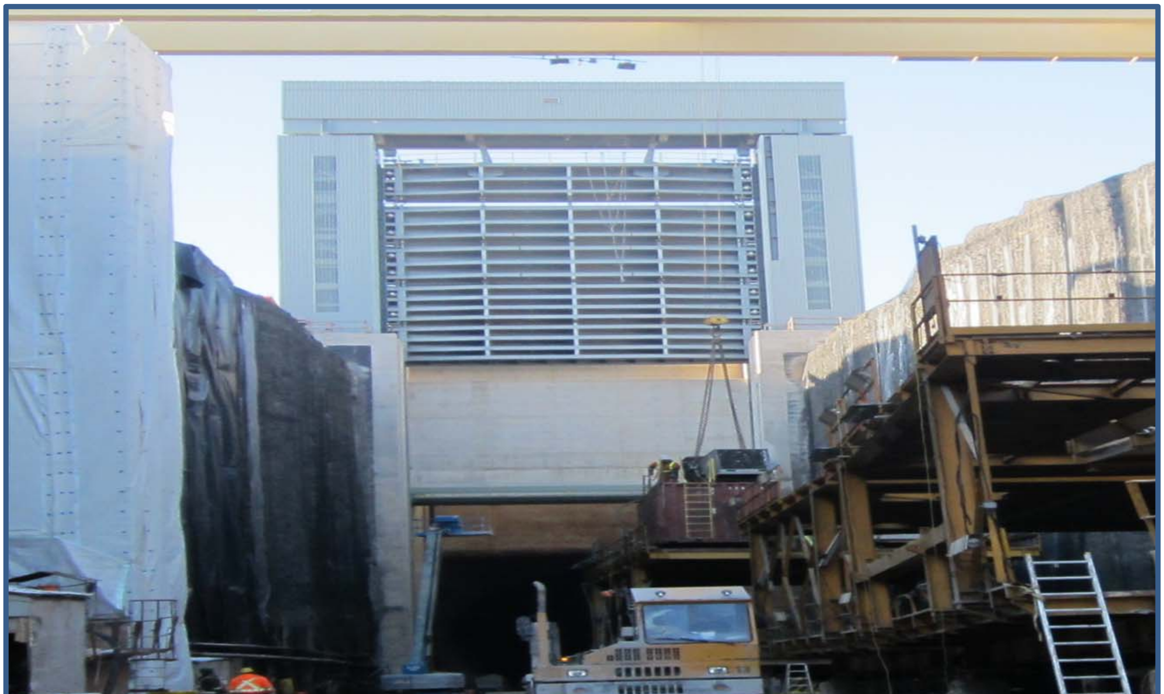
Laser scanner measuring deflection of concrete liner during interface grouting

Grouting carrier

Installation of rock support from TBM

Photographic Representations Niagara Tunnel

Installation of waterproof membrane



Outlet gate

OPG hereby authorizes Hatch Mott MacDonald / Hatch to submit Niagara Tunnel Project photos with your award application to ACEC/CCE and for use of these photos for associated marketing by ACEC/CCE. Please acknowledge that "Photos are provided courtesy of Ontario Power Generation Inc".

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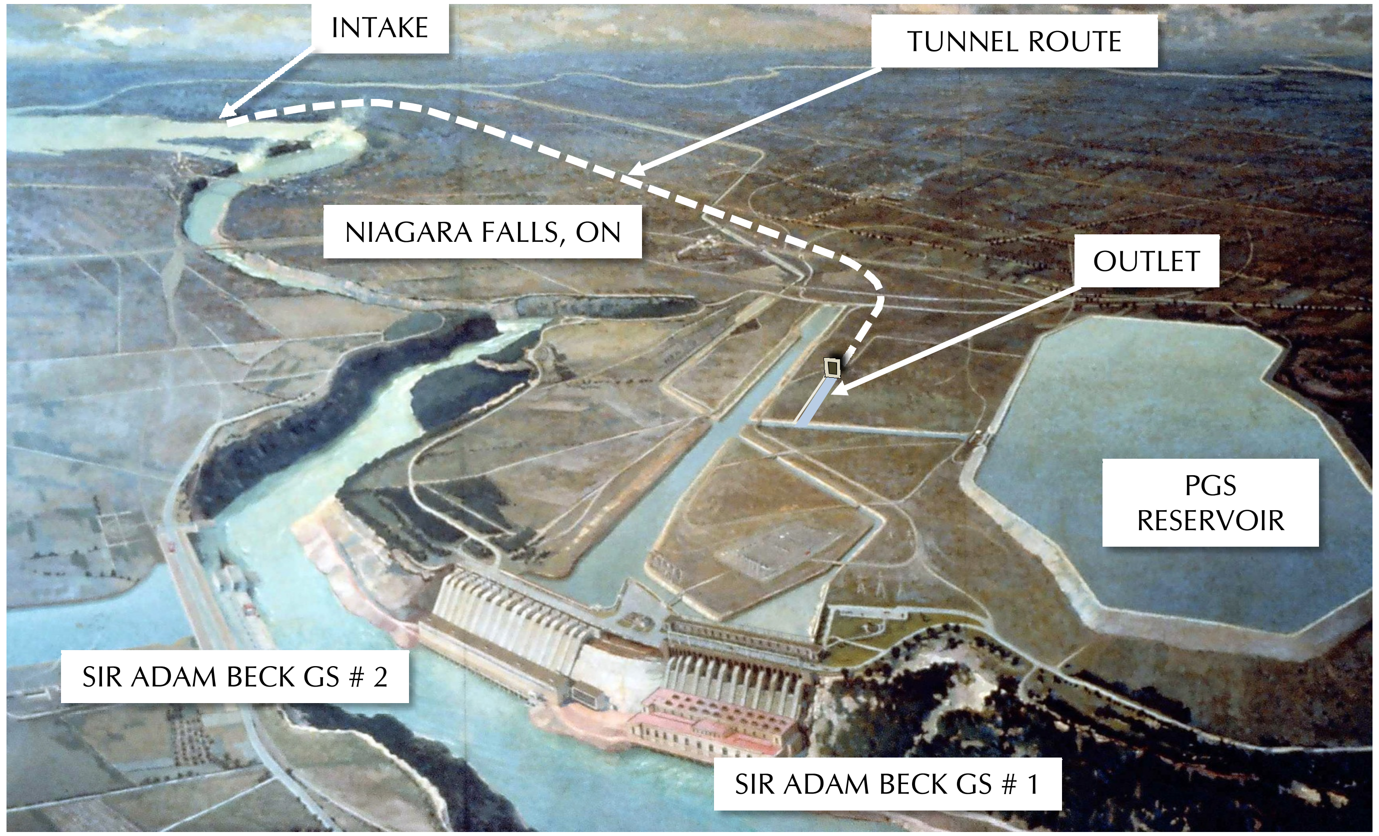
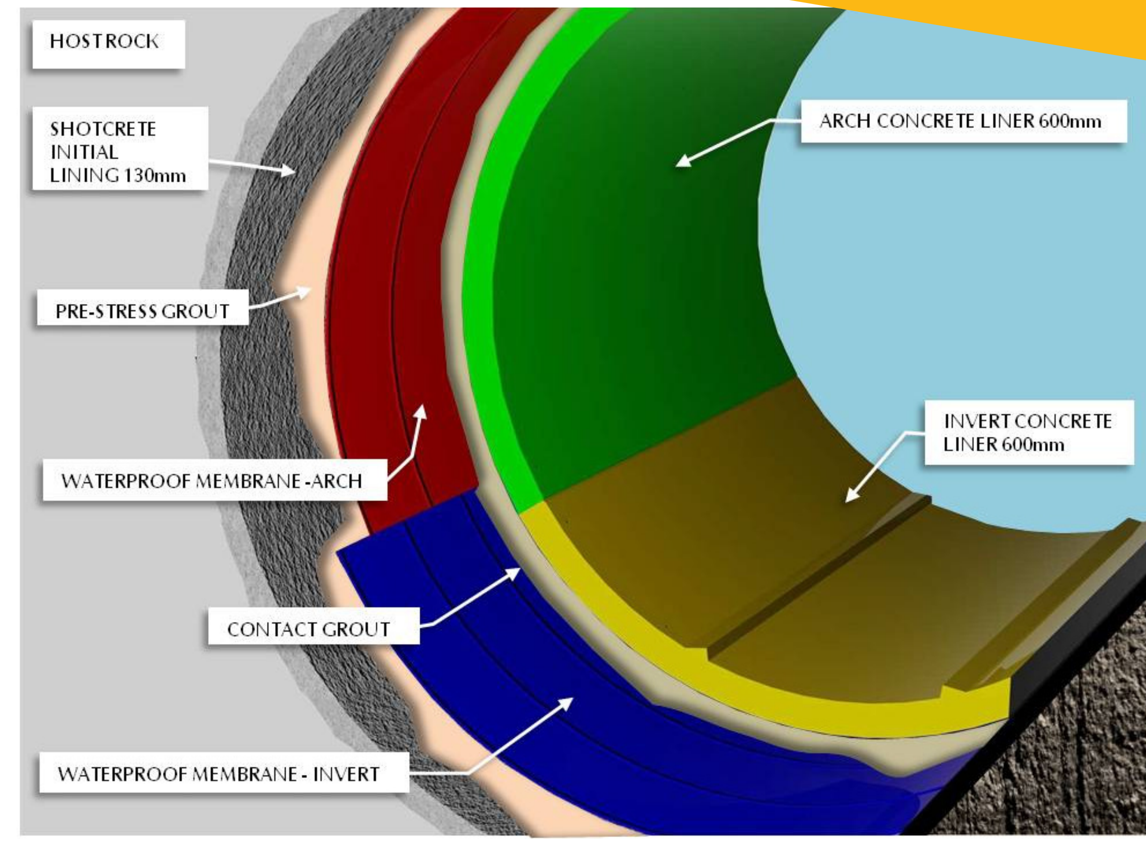
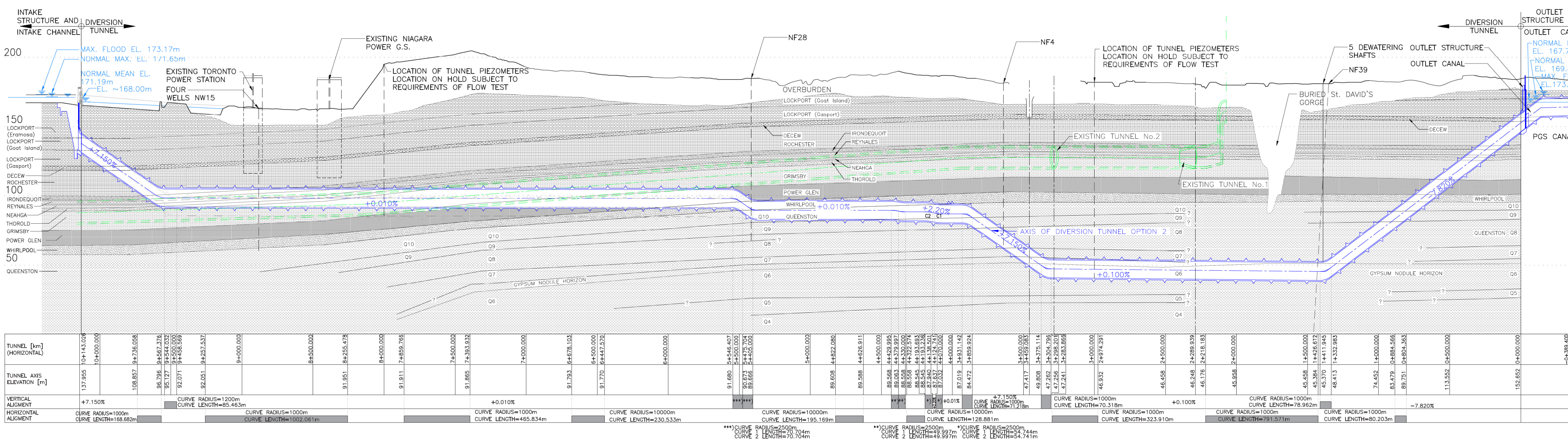


LOCATION



TUNNEL LINING



LONGITUDINAL SECTION