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Category: Water Resources

Port Mann Water Supply Tunnel

Seismic criteria demand innovation

Submitted by:

Ausenco

Client/Owner:

metrovancouver
SERVICES AND SOLUTIONS FOR A LIVABLE REGION

Other Consultants Involved:

McMILLEN JACOBS ASSOCIATES

Golder Associates

Project Summary

Metro Vancouver replaced a critical water supply pipe crossing beneath BC's Fraser River, to increase seismic and scour resilience and meet future demand. Ausenco's team designed the new tunnel though liquefiable soils, introducing many industry firsts, including: highest water pressure encountered in Canada; unreinforced ground support walls; and a concrete shaft and free standing pipe that significantly deform during an earthquake yet maintain water delivery, allowing the community and economy to recover quickly.

Project Highlights

Innovation

Metro Vancouver's (MV) existing Port Mann water pipe crossing was installed in the early 1970's in a "cut-and-cover" trench. The pipe was damaged by riverbed scour in 1997, had insufficient capacity for population growth, and had a high risk of failure during a relatively low level (1 in 475 year) earthquake.

Ausenco's team designed a deep tunnel, access shafts, valve chambers, and pipe mains to replace the crossing. Unique analysis and designs were required to overcome the challenges presented by the soft, wet, liquefiable soils surrounding the River.

Analysis indicated that soils around the exit shaft moved horizontally by up to 6m during a major earthquake, imparting enormous force on the shaft. Conventional concrete shaft designs could not withstand these forces – neither adding the maximum amount of reinforcing steel nor increasing the shaft diameter would increase the shaft strength sufficiently.

Ausenco designed the steel pipe to be self-supporting within the shaft so that, in reaction to the 6m soil movement, both the shaft and the pipe would yield, bend, and significantly deform, while maintaining performance (maintaining water delivery). This is the first use of such a shaft and pipe combined as a yielding system, and raised further challenges in pipe and shaft construction.

Standard grades of steel did not provide the specific ductility needed at the pipe yielding zones, so the team worked closely with steel suppliers to produce, test, and select specific steel for the pipe, to ensure it deformed appropriately without buckling.

The engineers used a special low friction slip liner to separate the shaft concrete from the ground support walls. Typically shaft concrete is placed directly against the support walls, which act as the external form. However, this interlocks the support walls with the shaft, inhibiting yielding - so the designers placed a low friction slip liner between the concrete shaft and the walls. Engineers conducted specialized testing to select a liner with the lowest friction. The team also broke with convention by designing the 80m deep ground support walls with no reinforcing steel, to limit their stiffness should composite behaviour occur between the support walls and the shaft.

Further innovation was introduced during construction, when ground freezing was implemented from a platform within the Fraser River, to allow repairs to a damaged TBM. Ausenco's team reviewed the contractor's plans and monitored the work to ensure safe, environmentally acceptable methods were implemented.

Complexity

In order to connect to existing water mains within MV's right of ways, the tunnel alignment ran through sand, silt, clay and glacial till, which spread laterally to differing extents during earthquakes. MV's criteria included continuous water supply following a major 1 in 10,000 year earthquake, beyond the current building code's 1 in 2475 year event. Ausenco's team determined the soil behaviour by analyzing recent earthquake data from six similar locations around the Pacific Rim, including Puget Sound, Chile, and Japan, and applying the ground acceleration data from these to the local soil properties (obtained through physical testing). The analytical models indicated soil movement of up to 6m would be generated near the surface during the maximum expected earthquake, and that resulting soil loads would exceed the shear strength of a traditional shaft.

The tunnel depth, 55m below grade, exposed the tunnel to high groundwater pressures and required an Earth Pressure Balance (EPB) tunnelling machine with provision for hyperbaric (high air pressure) entry into the cutter-head. Tunnelling withstood 600 kPa hydrostatic pressure, the highest for an EPB machine in Canada.

The tunnel crossed beneath an active rail yard and exited in a public park. The rail yard operation could not be disrupted, and the tunnel was to be "invisible" to park users on completion.

Also, the interconnecting pipe, between one valve chamber and existing pipe mains, crossed beneath a fish bearing stream, which could not be harmed.

The complex challenges presented by the tunnel location demanded innovative design.

Social and Economic Benefit

The tunnel increases both the reliability and capacity of MV's drinking water distribution to communities south of the Fraser River. Its capacity doubles that of the original crossing, allowing for projected population growth well beyond 2050. Its seismic resilience provides a stable, reliable water supply, which allows the community and local economy to recover, rebuild, and return to normal more quickly following a major earthquake.

The unobtrusive tunnel design allowed industry and community life to continue oblivious to its presence. The tunnel maintained a low profile both during and following construction, generating little public concern. Though the exit shaft sat within Coquitlam's Maquabeak Park, access to walkways around the park and to the public boat launch was maintained throughout construction. MV publicised the work, kept local residents and businesses well informed, and minimized any public or traffic disruptions. Co-ordination with two neighbouring construction projects, the Gateway Port Mann Bridge and the South Fraser Perimeter Road, ensured no issues between the sites.

The tunnel was, however, watched closely by those in the engineering and tunnelling community – the Tunnelling Association of Canada awarded the project "Innovative Tunnelling Project of the Year" in 2016, and the ACEC-BC granted it an Award of Excellence in 2017. The structural aspects of the design will be presented to the IABSE in 2017. The methods of construction and design innovations introduced in the Port Mann Tunnel expand the methods available for further tunnelling projects in Vancouver, Canada, and around the world.

Environmental Benefit

Ausenco's team included environmental specialists who prepared an environmental management plan and monitored construction activities to ensure the environment was protected. Construction introduced no detrimental effect to fish bearing streams nearby, to the Fraser River, nor to the general environment.

The tie-in pipe lines, connecting the tunnel to existing mains, were installed in cut-and-cover trenches which ran under both Bon Accord Creek (a fish bearing stream) and the new South Fraser Perimeter Road (Highway 17) which was then under construction. MV adjusted their schedule and installed new pipe mains beneath the highway three years before the tunnel was completed (four months before the highway was completed) to avoid disruption to traffic. The tie-ins were also installed during low flow conditions in Bon Accord Creek. Environmental engineers provided guidance and monitored construction activities when the creek was temporarily diverted, using cofferdams and a pump system, to allow installation of the pipe underneath it. The work included a fish capture and release program and restoration of the creek with Coho spawning beds, to ensure the creek's aquatic life was unharmed.

The engineering team also provided an archaeological assessment to ensure no historic artefacts would be disturbed during the work. None were.

The final steps of the project included site restoration – Maquabeak Park was returned to its original condition, and the Surrey site was reforested and replanted with native flora.

Meeting Client's Needs

The Port Mann Tunnel design fully met MV's needs and expectations which included:

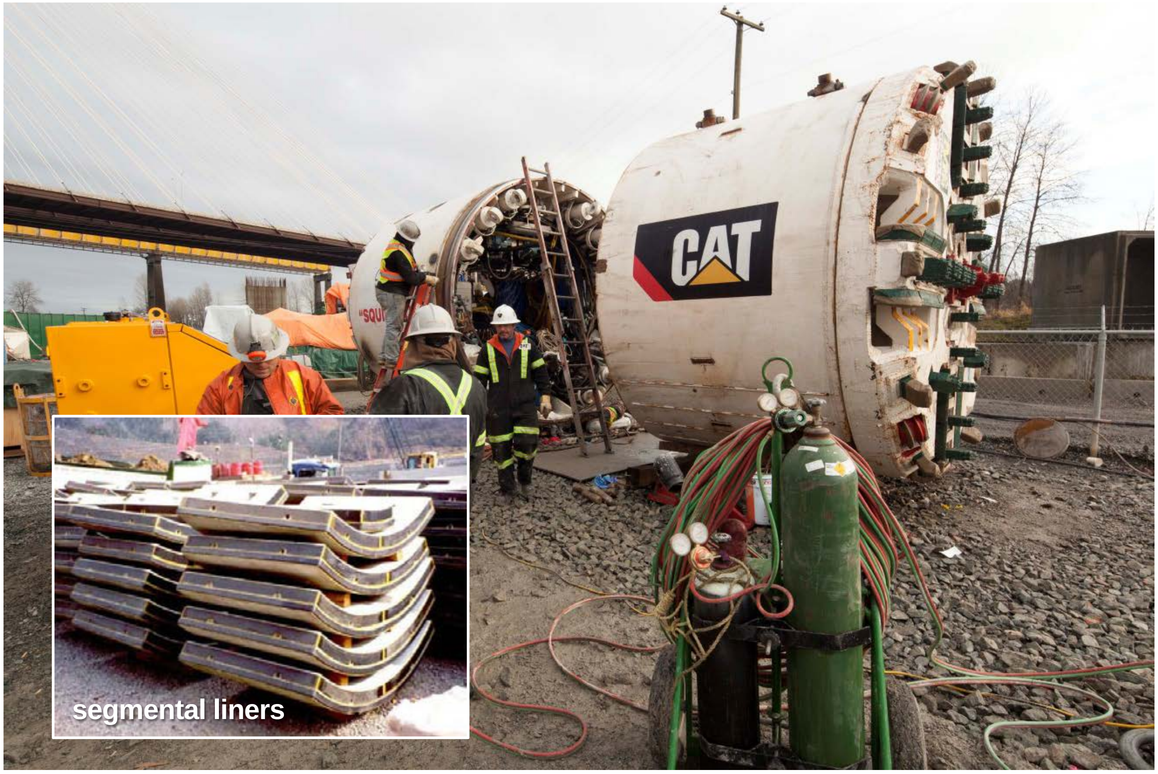
- 100 year design life;
- Pipeline remains operational following the maximum credible earthquake (1 in 10,000 year event) over the design life;
- Tunnel depth avoids any impact of river bed scour;
- Capacity to double water flow for future population growth;
- Minimal disruption to the community and to MV's operations;
- Compliant with building codes, electrical codes, and AWWA standards – while these codes were met, the codes do not consider the stringent requirement to remain operational following a 1 in 10,000 year earthquake. The engineering analysis described above was utilized to exceed standard code requirements;
- Safety – the tunnel and valve chamber design meets or exceeds safe work requirements, and allowed the work to be constructed safely;
- No impact on surrounding properties;
- Environment and sustainability - the work was conducted without detrimental environmental incident, with no permanent loss of public space in Maquabeak Park, and with no loss of natural habitat.

As well, the project was completed within the $240M budget.

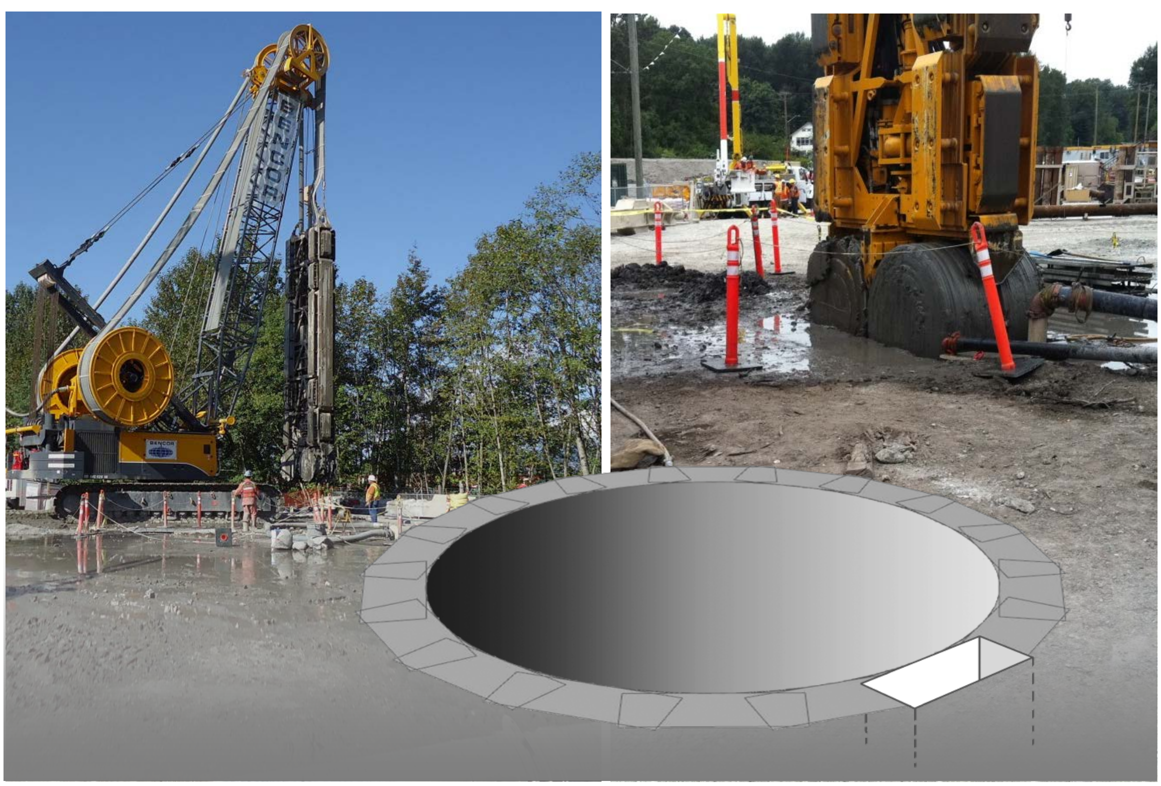
Ausenco

Project Details

North Shaft, Coquitlam:	5m Inside Diameter, 1.5m thick walls, 65m deep
South Shaft, Surrey:	11m Inside Diameter, 1m thick walls, 55m deep
Pipe in Shafts:	1.6 and 2.1m diameter, 25mm thick wall, free standing
Tunnel:	3.5m bored diameter, 1km long, 55m below grade. Lined 250mm thick precast concrete segments, with internal steel pipe, 2.1m diameter, 25mm thick wall, grout encased.
Tunnel Boring Machine:	Caterpillar EPB, 80m long; 640kW drive, 1.7m stroke, 1,800 tonnes thrust

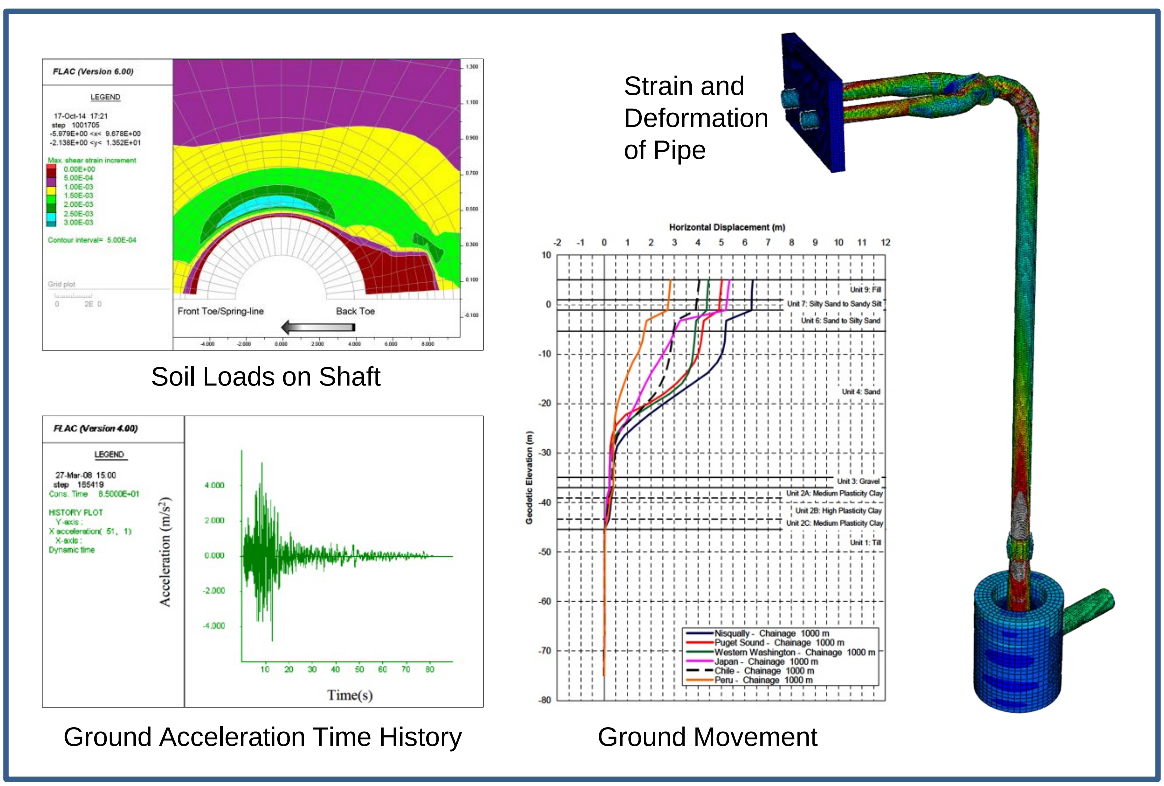


Cutterhead and drive section of the TBM being prepared for lowering to tunnel. The 80m long TBM, delivered in 3m to 8m sections, was assembled at the base of the 11m diameter shaft as the tunnel advanced.

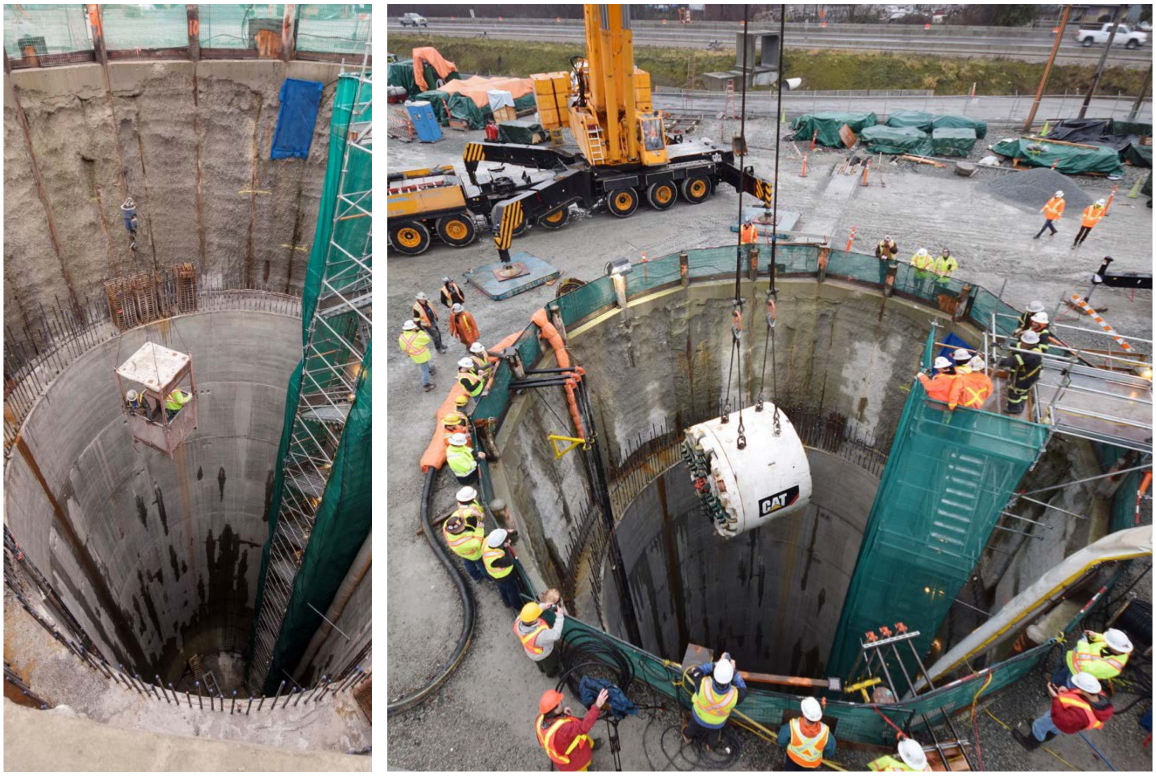


Ground support walls, 70m to 80m deep were constructed for each shaft using a Hydromill.

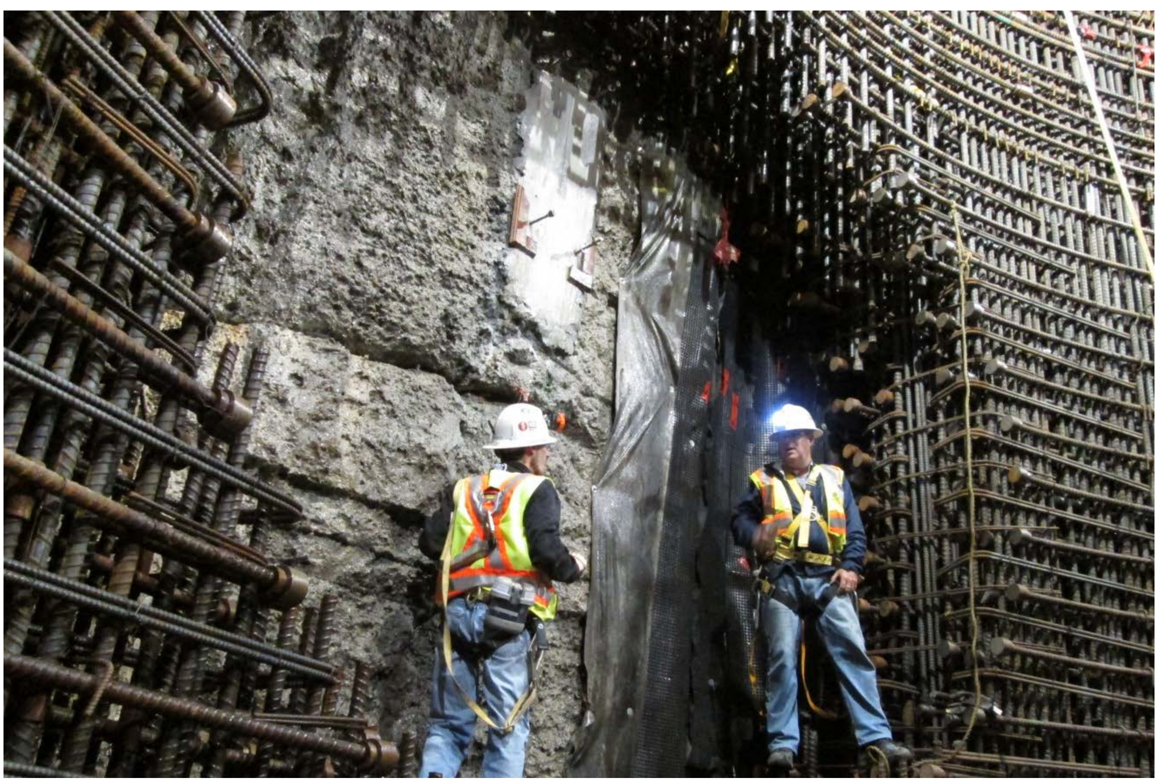
Bon Accord Creek diversion – fish capture underway, cofferdam set up to divert the flow, and restored creek with Coho spawning beds.



Analysis models determined the expected ground behaviour in a 1:10,000 earthquake, and response of the shaft. Predicted soil movements of up to 6m, result in up to 2.5m movement at the top of the shaft pipe.



Work crews and TBM cutterhead entering the south shaft.



Reinforcing at shaft to tunnel connection. Reinforcing steel was specified with high, low, or combined ranges of strength depending on location to ensure the shaft yields and remains operational following a major earthquake.

Pipe elbow at bottom of shaft. Inset: lowering shaft pipe into position. The pipe is supported only at the bottom of the shaft and at the valve chamber end wall – a 60m span.

3.5m dia. tunnel after boring completed and prior to installation of water supply pipe. The concrete segments seen here withstand 6 bar (600 kPa, 80 psi) external ground pressure.

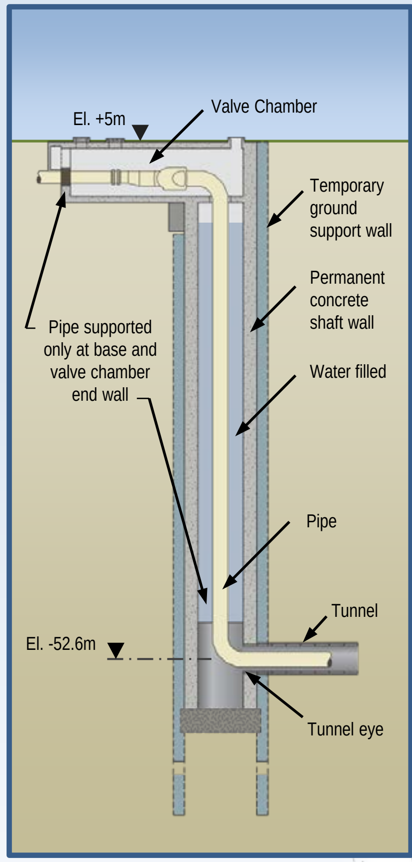
Pipe installed in the valve chamber end wall. The pipe is supported only at this wall and at the bottom of the shaft.

Coquitlam's Maquabeak Park restored after construction. The Fin Donnelly Memorial Tree, just left of center, was preserved throughout the work.

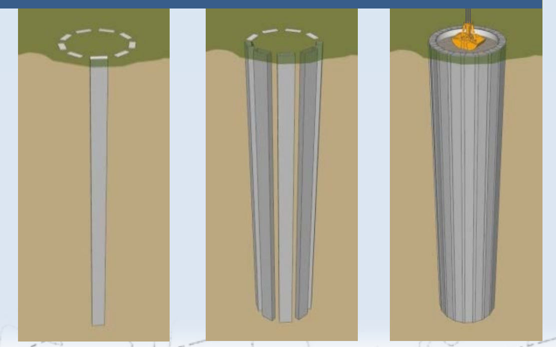
Port Mann Water Supply Tunnel

The new water supply tunnel is capable of withstanding a 1 in 10,000 year seismic event. Construction encountered ground water pressures of up to 6 bar, the highest of any Canadian soft ground tunnel to date. Using both linear and nonlinear geotechnical and structural analysis (FLAC, ABAQUS, SAP2000) this innovative design includes a 60 metre deep vertical concrete shaft around steel pipe designed to safely yield to some 15 times past its elastic limit and still deliver water.

Shaft Details



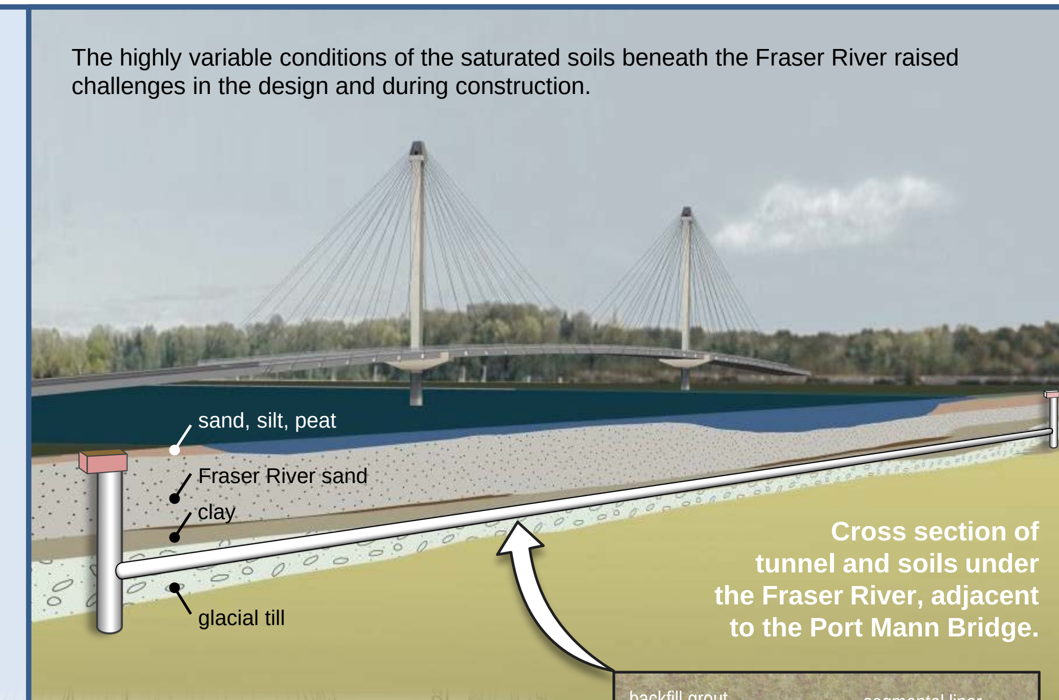
Ground Support Walls for the Shafts

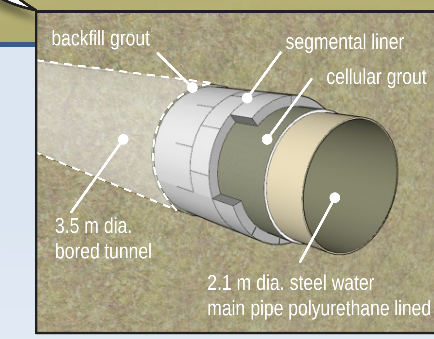


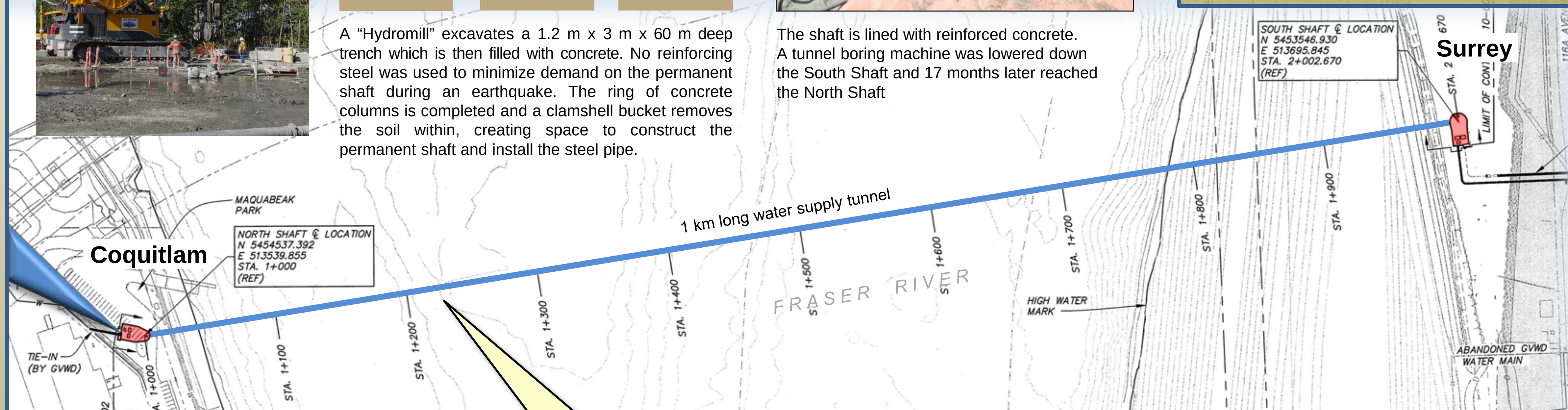
A "Hydromill" excavates a 1.2 m x 3 m x 60 m deep trench which is then filled with concrete. No reinforcing steel was used to minimize demand on the permanent shaft during an earthquake. The ring of concrete columns is completed and a clamshell bucket removes the soil within, creating space to construct the permanent shaft and install the steel pipe.

The shaft is lined with reinforced concrete. A tunnel boring machine was lowered down the South Shaft and 17 months later reached the North Shaft

The highly variable conditions of the saturated soils beneath the Fraser River raised challenges in the design and during construction.



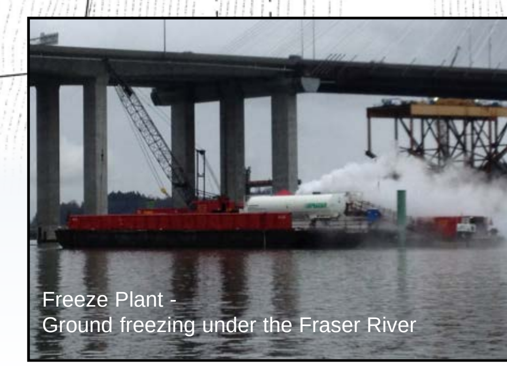




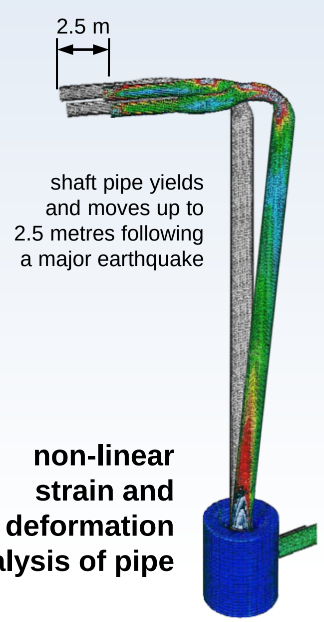
Viewing platform built in Maquabeak Park to offset loss of park space during construction

GROUND FREEZING FOR TBM REPAIR

Tunnelling stopped 200 meters short of the North Shaft for major repairs to the Tunnel Boring Machine. Liquid nitrogen was injected through bore holes to freeze the ground around the cutterhead beneath the Fraser River. This held back the significant pressure of ground water and soil. The frozen tunnel muck was then removed through the excavation chamber and the repairs were completed.



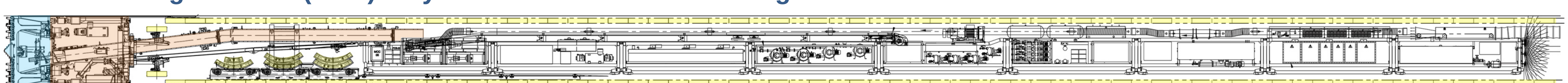
Freeze Plant - Ground freezing under the Fraser River



shaft pipe yields and moves up to 2.5 metres following a major earthquake

non-linear strain and deformation analysis of pipe

Tunnel Boring Machine (TBM) fully assembled - 80 metres long



The TBM was lowered down the 11m diameter shaft in sections and assembled at the base as the tunnel advanced.

Delivering clean, safe drinking water to communities south of the Fraser River following a major earthquake.