Mamquam Power Tunnel - Design and Construction

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ABSTRACT

The 260 m head Mamquam hydroelectric project constructed between 1994-1996, near Squamish, B.C. comprises a diversion weir/sediment sluice intake structure and a surface powerhouse with two 25 MW vertical shaft Francis units. The power conduit consists of a 426 m long drill and blast upper tunnel and a 2.6 km long machine bored lower tunnel, connected by a 158 m high raise bore shaft. This project represents the first use of a tunnel boring machine (TBM) in the very hard rocks of the Coast Range intrusives in B.C., providing cost and schedule advantages over drill and blast methods. Hydraulic jacking tests were conducted to establish the length of steel liner required upstream of the powerhouse. The section of steel liner where the lower tunnel passes beneath the Mamquam canyon was eliminated due to enhanced rock stresses which exceeded those predicted by normal overburden loading assumptions. The power tunnel has now been in service for over one year and initial performance is excellent.

Project Description

The project is located about 60 km north of Vancouver and 4 km east of the town of Squamish, B.C. (Figure 1). The Mamquam basin area of 273 km^2 above the intake is mostly forested and very rugged and receives 132 cm of average annual precipitation. River flows vary from a typical minimum average of 13 m^3/s in February to a maximum average of 40 m^3/s in June, with a 1:500 year design flood of 600 m^3/s. Full supply level (FSL) at the intake is at elevation 297 masl.

The run-of river project develops 260 m of head as the river drops through a series of waterfalls and rapids through a 3 km long deeply incised post-glacial canyon. The project facilities include:

- a two bay concrete diversion weir with rubber dams for forebay control and a radial gated 10 m wide sluiceway immediately upstream of the canyon
- a left bank intake structure with a design capacity of 24 m^3/s equipped with trashracks and sediment basin
- a 426 m long unlined, "D" shaped upper tunnel 3.6 m in diameter
- a 158 m deep unlined vertical shaft 3.3 m in diameter

- a 2575 m long unlined circular lower tunnel 4.1 m in diameter with a 434 m long, 2.1 m diameter free standing steel penstock upstream of the powerhouse
- a right bank surface powerhouse in a 25 m deep rock cut containing two 25 MW vertical shaft Francis units (installed capacity of 56-58 MW), with a 35 m long tailrace channel
- a 4.6 km long 69 kv transmission line connecting to the BCH transmission line substation at Squamish

The net head of 238 m and a plant factor of 0.57 yields an average annual power generation of 280 GWH (250 GWH firm) at a flow of 24 m^3/s. Construction began in July 1994, with commissioning in November 1996 at a total cost of approximately $70 million (Canadian). The project is owned and operated by Northern Utilities Incorporated of Vancouver, B.C.

Site Geology

The project is situated in the Coast Plutonic complex. The oldest rocks comprise granitic to intermediate intrusives and minor volcanic rocks of Jurassic age (Lynch,1990). These are overlain unconformably by metamorphic rocks of the Gambier Group of early Cretaceous age. Later granitic intrusions of mid-Cretaceous age, exposed to the south and west of Squamish, resulted in the deformation of the older plutonic rocks and the overlying Gambier complex. North trending, steeply dipping foliation and shear structures are found within the intrusives and especially within the weaker cover rocks.

Tertiary and Quaternary volcanic activity centered on the Garibaldi volcanic complex located about 15 km north-northeast of the project area resulted in a series of basalt to rhyodacite lava flows, pyroclastics and minor intercalated sediments. The Pliocene-Recent aged Ring Creek lava flow of dacitic composition occupies the north side of the Mamquam valley and covered the ancestral Mamquam valley which was infilled with older glacial and fluvial deposits. The lava flow split the drainage of the valley. The Mamquam River and Ring Creek have both incised deep valleys and canyons respectively along the south and north sides of the lava flow. Subsequent post-glacial erosion has exhumed the basement complex forming the south (left bank) side of the Mamquam valley, which is overlain by a thin veneer of till. The steep lava cliffs of the Ring Creek lava flow form the north (right bank) side of the Mamquam valley.

Figure 1 presents a plan of the project area geology and the longitudinal section along the power tunnel. Sheared metavolcanics of the Gambier Group are found in the intake and upper tunnel area. The surface trace of the Gambier/intrusive contact was difficult to establish due to the similarity of the sheared dioritic intrusive rocks and the chloritized and sheared andesitic rocks of the Gambier Group. The shaft, lower tunnel and powerhouse are located within the plutonic rocks, which comprise massive to widely jointed quartz diorites with north trending, steeply dipping foliation shear zones up to 5m wide. The lower end of the Ring Creek lava flow is located about 600 m east of the powerhouse. The slope between the base of the lava flow and the powerhouse is composed of glaciofluvial outwash overlying glacial deposits which infilled the preglacial valley under the lava flow. The fluvial and glacial materials under the lava flow act as an aquifer, resulting in numerous spring discharges along the base of the lava and the slope above the powerhouse.

Site Investigations

In 1989, preliminary studies investigated the option of a right bank tunnel under the Ring Creek lava flow. This was rejected due to the lack of information on the basement bedrock topography, potential for water inflows and poor tunneling conditions. Several left bank tunnel schemes within the intrusive rocks were considered during feasibility studies including vertical shafts, inclined tunnels, and underground powerhouse options. In 1991, a left bank intake and tunnel alternative, with a right bank powerhouse was adopted after reconnaissance geological mapping and seismic surveys. In 1993 additional geological mapping and drilling of seven holes along the tunnel route formed the basis for the turnkey design-construct contract awarded to the Kiewit/ Acres team in 1994.

Additional investigations conducted by Kiewit/Acres for final design and construction included seismic refraction surveys, test pitting, Becker drilling and sampling of glacial overburden deposits , diamond drilling, point load testing and water pressure testing of bedrock at the powerhouse, intake and at the location of the vertical shaft. The location of the diamond drill holes along the power tunnel are shown in Figure 1. Geological mapping to confirm the distribution of the major rock types, particularly the location and orientation of the Gambier/intrusive contact was carried out in the intake/upper tunnel area.

Tunnel Layout and Sizing

The original alignment recommended in the 1991 feasibility studies and investigated in 1993 was based on drill and blast method of construction for a 3m diameter tunnel. During final design for construction, the option of using a tunnel boring machine (TBM) was found to offer savings over conventional drill and blast excavation and minimized head losses as well. The alignment of the tunnel was changed to minimize the length of tunnel within the Gambier metavolcanics, which were considered to be unfavorable for machine tunneling. The location of the vertical shaft was critical in defining the extent of the lower machine bored tunnel and it was located about 60 to 80 m south of the contact to ensure that the lower tunnel and shaft were entirely within the intrusive rock.

The height of the raise bore shaft was reduced by driving the upper tunnel at a 10% down grade from the intake to the shaft. The lower tunnel was driven at a 2% up grade from the powerhouse to maximize the amount of rock cover over the tunnel at the Mamquam valley sub-crossing. Once the tunnel passed the Mamquam valley the grade was increased to 3%.

The sizing of the tunnel diameter was dictated by the rock conditions, tunneling equipment and hydraulics. The upper tunnel diameter of 3.6 m resulted in a velocity of 2.07 m/s. A concrete invert also helped to limit head losses along the relatively rough tunnel walls. The lower tunnel, bored at 4.1 m was based on the TBM cutter head selected to suit the high strength intrusive rocks, resulting in a velocity of 1.82 m/s. Shaft diameter was somewhat constrained by the need to bring the raise bored cutter head in through the lower tunnel. The smaller diameter results in a velocity of about 2.8 m/s. Head losses in the machine bored portions of the tunnel were estimated to be about 33% of those in the drill and blast section, on a per metre basis.

Cover Criteria and Length of Steel Liner

The hydraulic head in the power tunnel is adequately confined by the weight of the surrounding rock in the portion between the intake and the Mamquam River crossing. However at the valley crossing , the rock cover is a minimum of 50 m (Figure 1) which would theoretically be insufficient to contain the 250 m head of water in the tunnel at this point. The portion of the tunnel upstream of the powerhouse also lacks sufficient cover. Initial estimates based on the empirical Norwegian cover criterion (Brekke and Ripley, 1987) recommended that the steel liner extend for 500 m upstream of the powerhouse and a minimum of 135 m under the valley. To confirm the minimum in situ stress levels around the tunnel, a program of hydraulic jacking and fracturing tests were planned.

Rock Support Requirements

Feasibility level investigations in 1993 predicted generally good to excellent tunneling conditions in the intrusive rocks. Rock strengths ranged from 100 to 300 Mpa (14,500 to 43,500 psi). The north trending steeply dipping foliation shear zones are the dominant structural fabric within the intrusives. These features form zones of closely spaced joints several metres wide, sometimes associated with thin clay gouge seams. Joint continuity is greater than 10 m. The intervening rock mass is massive to widely jointed, with rough, discontinuous joints. Down hole packer testing in surface drill holes measured hydraulic conductivities in the order of 10^{-6} cm/s. The foliation shear zones were expected to be associated with zones of moderate inflow to the tunnel. The use of the TBM was expected to result in a largely self-supporting tunnel due to the favorable orientation of the foliation normal to the tunnel axis.

Fair to poor tunneling conditions were expected in the Gambier metamorphics which suffered the greatest disturbance by shearing and folding. Local zones of highly fissile phyllite and schist and sheared metavolcanics were predicted in the upper tunnel. Point load strength tests ranged from 25 to 50 Mpa (3,625 to 7,250 psi). A fault containing a 1 m wide zone of gouge and frequent subvertical shears was mapped along the logging road above the upper tunnel and was predicted to be encountered in the tunnel. Hydraulic conductivities were low (10^{-5} cm/s), but water losses when drilling across fault and shear zones indicated that moderate amounts of inflow could be expected locally.

Drill hole DH 94-1 confirmed that the shaft would be located entirely within the intrusive rock. However zones of fair to poor quality rock was predicted in the lower part of the shaft, with a minor amount of very poor quality rock associated with four shear zones dipping at about 70°, ranging in width from 1 to 3 m. Seepage was also expected to be associated with the shear zones found in the lower portion of the shaft.

The tunnel was unlined, with rockbolt and shotcrete support as necessary, using resin grouted and tensioned threadbar bolts and steel fibre reinforced shotcrete (SFR). Bolt spacing and shotcrete thickness could be varied depending on ground conditions encountered. In the raise bored shaft, pattern bolts and shotcrete were required in the vicinity of the four steeply dipping shear zones, with spot bolting used over most of the rest of the shaft walls. In the lower tunnel generally good to excellent rock quality was predicted. Spot bolting in the crown could be done from inside the TBM over a restricted area.

Clay seams associated with the foliation and shear structures were recognized as potentially erodible under tunnel operating conditions (Spencer et al, 1964, Brekke and Ripley, 1987). These features were protected with 50 mm of SFR shotcrete after mapping of the completed tunnel.

Tunnel Construction

Upper Tunnel

Tunneling was completed after excavation of the intake portal area. A Gardner Denver two boom drill jumbo and two Gardner Denver scooptrams (2.3 and 3.8 m^3) were used. Drilling and blasting was done in 3.4 m rounds. A pattern of three, 2 m long resin anchored rockbolts in the crown at 1.5 m centres plus 25 mm shotcrete as required was used during construction. The first 305 m (to tunnel Sta 0+305) was in subvertically dipping, moderately foliated, blocky jointed, medium strong metavolcanic andesite and rhyolite. Subhorizontal joints caused overbreak in the crown and haunch in some areas giving a flat roof. Joint surfaces were usually slickensided and chloritized. Thin clay infilling was common.

The fault zone expected from the surface mapping was encountered in the tunnel about Sta 0+253 m. Twelve subvertical shears, typically 0.2 m wide which trended about N10°E crossed the tunnel at about 40° to its axis over a total length of 45 m. The clay mylonite zones were flanked by closely jointed water bearing wall rock. A program of grouting was carried out through three fans of radial holes to control the inflow.

The Gambier/intrusive contact was oriented at 83° dip/ 295° dip direction, with no significant alteration or disturbance, The intrusive rocks from Sta. 0+305 to the end of the upper tunnel were generally strong to very strong quartz diorite and monzonite, grading locally to granodiorite, Rock quality was generally poor for the first 40 m past the contact but improved thereafter and was generally good in the last 80 m of the drive. The height of the last 20 m of tunnel was increased to accommodate the raise boring equipment which would be collared on top of the shaft. At the end of the drive, tunnel seepage was about 240 l/min, mostly from the metavolcanics between Sta. 0+070 and 0+305. Seepage flow steadily decreased as the rock mass above the tunnel became drained.

Following completion of tunnel excavation, additional rock support was installed after geological mapping and inspection. Additional bolts and shotcrete were required to improve stability during operation and to treat the potentially erodible clay seams and closely jointed areas. SFR shotcrete was used to provide a minimum of 50 mm cover to erodible features and to thicken other shotcreted areas.

Lower Tunnel

The machine bored lower tunnel drive was constructed using a Robbins TBM with 33 cm dia. cutter discs. The TBM and its 60 m of trailing gear were set up in an enlarged "starter tunnel" section of the lower tunnel which was excavated for the first 30 m upstream of the powerhouse. The remainder of the trailing gear outside the downstream portal was set up in a 20 m slot excavated between the portal and the upstream side of the powerhouse excavation. This area also housed the steel superstructure supporting the Airdox conveyor system used to transport the rock cuttings from the TBM face to the rock disposal area.

After boring through the first 133 m of rock, the TBM encountered an unexpected 22 m wide buried valley, infilled with dense glacial till. In order to progress through this soft ground zone, a small bypass tunnel was blasted around the TBM cutter head to allow access to the face. Mining then progressed using steel ribs and SFR shotcrete.

Tunneling conditions in the remainder of the lower tunnel were generally better than predicted, with about 95% of the length in good quality, widely jointed, tight intrusive rock. The steeply dipping shear zones were encountered at a spacing of 10-50 m along the tunnel, but were mainly tightly interlocked with thin (<50 mm) clay seams, oriented close to right angles to the tunnel drive, with little to no overbreak. Seepage into the lower tunnel occurred mainly from the foliation shears in the upstream half of the tunnel. Final rock support was added after completion of tunneling and mapping to provide additional support in the fault zone area and to cover potentially erodible clay seams.

Shaft

The Robbins 1236 raise boring equipment was collared in the upper tunnel and the shaft was drilled in two passes. The initial pass at about 0.4 m diameter formed a pilot hole for the raise bore drill stem. The cutter head then reamed the full shaft diameter. The spoil from the raise bore was collected in the lower tunnel at the base of the shaft and conveyed to the surface using the TBM cutter head and mucking conveyor system. An Alimak platform was used to conduct mapping and inspection of the shaft and identify rock support requirements. Rock support was installed from the top down for safety. Most of the upper half of the shaft required only local spot bolting to support wedge failures along steeply dipping shear features, The upper half of the shaft was relatively dry. Increasing seepage with depth occurred in the lower half of the shaft due to the presence of the shear zones. Pattern bolts and chainlink mesh were used to prevent raveling of the closely jointed rock in this area. Pattern bolts and shotcrete were installed over about 15% of the shaft length. In total, the support quantities were about 20% higher than those predicted from the rock quality in BH 94-1.

Penstock Steel Lined Section

Hydraulic jacking and fracturing tests conducted in the tunnel sidewall and invert confirmed that the penstock steel liner would be required to a point about 434 m upstream of the powerhouse. Measurements made in the tunnel at the Mamquam valley crossing found that the minimum principal stress field was enhanced by the steep notch-like geometry of the canyon above the tunnel and provided a minimum factor of safety of 1.3 against hydraulic jacking. Parametric boundary element stress analyses confirmed the magnitude of the stress fields under the valley and at the upstream end of the penstock. The decision to eliminate the steel liner under the valley was made based on the test results and the presence of low permeability, excellent quality, massive to very widely jointed rock under the valley.

The penstock was designed as a 22 mm thick, 2.1 m diameter free standing steel liner inside the 4.1 m diameter lower tunnel. A 20 m long concrete plug was constructed at the upstream end of the steel liner.

Initial Performance

The project was commissioned on November 25,1996 and was inspected after about one year of service. No significant abnormalities were noted. Rock traps located in the upper tunnel next to the shaft and in the lower tunnel upstream of the penstock were sized based on the area of exposed rock and estimates of spalling likely to occur during operation. The lower tunnel rock trap (72 m^3) was about 75% filled with sand and fine gravel, which originate from the river during high flood levels as suspended sediment. Similar conditions were noted in the upper tunnel rock trap (45 m^3) which was about 50% filled. Occasional rock spalls up to 0.4 m size were noted on the tunnel invert and occurred as a result of unbalanced water pressures during tunnel unwatering. The river crossing section was dry, with no signs of joint dilation, confirming that the existing rock is providing adequate confinement. Total estimated seepage inflow was 4200 l/min mainly from water bearing shear zones in the upper half of the lower tunnel. The upper tunnel was dry, indicating that the surrounding rock mass is now being drained by the upper tunnel. The shotcreted areas showed no signs of cracking or spalling.

Conclusions

The Mamquam power tunnel provides an interesting case history of tunneling in the Coast Range intrusives and metavolcanic rocks of the Cordillera. The project involved a machine bored tunnel and raise bore in the intrusives and a drill and blast tunnel which traversed the metavolcanic/intrusive contact, providing opportunities to assess the effectiveness of each method in their respective geological environments.

Favorable tunneling conditions were provided by the orientation of the tunnel normal to the main foliation and shear fabric in the rock mass. In both the upper and lower tunnels, supplementary shotcrete was required to protect the potentially erodible weak seams in addition to the shotcrete applied for excavation support.

Hydraulic jacking and fracturing tests proved cost effective in reducing the overall steel liner length predicted using empirical criteria in the powerhouse and valley crossing area, where the complex stress conditions provided additional confinement.

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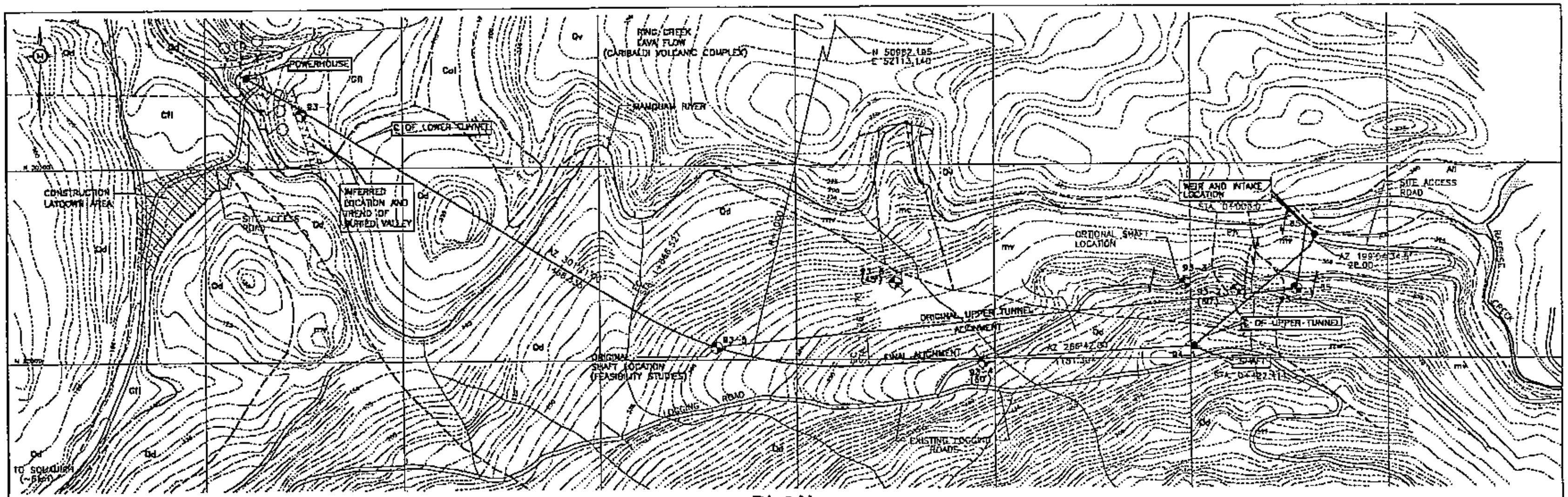
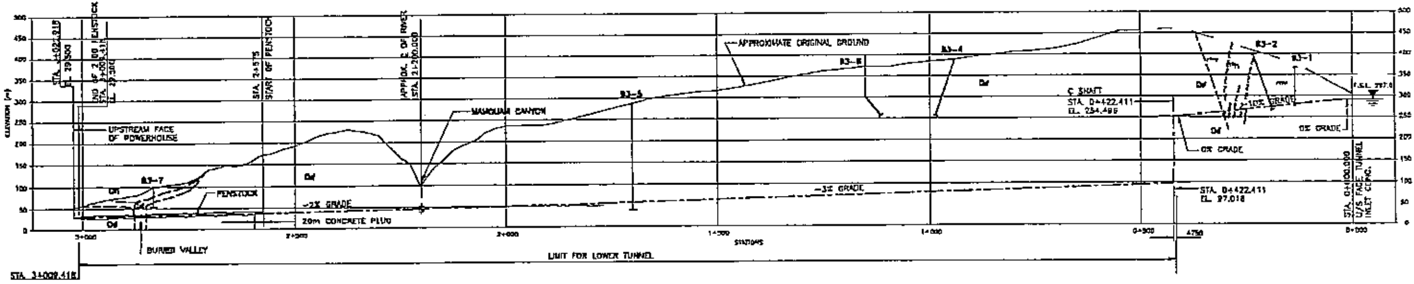


PLAN



TUNNEL ℄ PROFILE

LEGEND

QUATERNARY

Recent:

All	Alluvium and undifferentiated river deposits.
Cfl	Glaciofluvial deposits. Outwash and terraces.
Col	Colluvium derived from Garibaldi lava flows.
Qv	Garibaldi volcanic complex—dacite lava flows (Ring creek lava)

Pleistocene:

Gd	Glacial drift, till veneer, undifferentiated.

Early Cretaceous:

(Gambier formation – metamorphic assemblage)

mv	Andesite – rhyolite (greenstone).
Ph	Phyllite to schist
mc	Conglomerate, massive, rounded clasts.

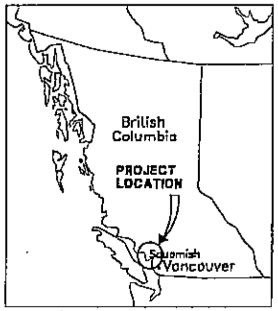
Jurassic (Intrusives)

Qd	Quartz diorite, monzonite, quartz monzonite, granodiorite.

0 50 100 150 200 250 m
Scale 1 : 5000

SYMBOLS

- - - - - - - -	Approximate geological boundary
⊣ ⊣	Foliation (inclined, vertical)
∼∼∼∼	Shear zone
←○	Seepage
93-7 ⊕ ● 94-1	Tunnel drill hole locations



LOCATION PLAN

GENERAL ARRANGEMENT AND GEOLOGY

Figure 1