

Waneta Expansion Project – Penstock Tunnels

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ABSTRACT

The Waneta Expansion Project (WAX) is a \$900 million, 335 megawatt, hydroelectric project currently under construction on the Pend d'Oreille river near the city of Trail, British Columbia. This project includes construction of a second power house and a 10 km transmission line to share the hydraulic head created by the existing Waneta Dam. The WAX is currently 1.5 years into construction with a projected completion in mid 2015.

Redpath/FKCI Waneta Tunnelers (RFK) was sub-contracted by the heavy civil contractor, ASL-JV, an Aecon/SNC-Lavalin joint venture, to excavate two new, parallel intake tunnels each approximately 215 meters in length with an 11 meter finished diameter and inclined on a 17% grade. Once the penstock tunnels are excavated a 10.5 meter diameter cast in place concrete liner will be installed in each tunnel. This paper will provide details about the top heading and bench excavation method used to develop the parallel intake tunnels and describe the challenges and benefits associated with using a self-advancing tunnel form on a 17% slope.

RÉSUMÉ

Le projet d'expansion hydroélectrique Waneta (WAX), présentement en construction sur la rivière Pend d'Oreille située à proximité de la ville de Trail en Colombie-Britannique, représente un investissement de 900 millions pour une puissance additionnelle de 335 mégawatt. Ce projet comprend la construction d'une seconde centrale et d'une nouvelle ligne de transmission de 10km qui permettra ainsi un partage de la charge hydraulique créée par l'actuel barrage Waneta. La fin des travaux, débutés depuis maintenant plus d'un an et demi, est prévue pour le printemps 2015. Redpath/FKCI Waneta Tunnelers s'est vu octroyer un contrat de sous-traitance par l'entrepreneur de Grands Travaux de génie civil ASL-JV, une coentreprise formée par Aecon et SNC-Lavalin, pour l'excavation de deux nouveaux tunnels parallèles d'une longueur de 215 mètres chacun pour un diamètre excavé de 11 mètres le tout sur une inclinaison de 16%. Une fois les travaux d'excavation des tunnels terminés ces derniers seront bétonnés afin d'obtenir un diamètre final de 10,5 mètres. Ce document fournira les détails relatifs à la méthode d'excavation en deux temps avec percée frontale et banquettes utilisées pour les travaux des tunnels de même que les défis et les avantages associés à l'utilisation d'un système de coffrage coulissant sur un plan incliné à 17%.

INTRODUCTION

The Waneta Expansion Project (WAX) is located near the existing Waneta Dam site at the confluence of the Pend d'Oreille and Columbia Rivers approximately 10 km south of Trail, BC, Canada. The WAX owners consist of a partnership between Fortis Inc., Columbia Basin Trust, and the Columbia Power Corporation. This design build project was awarded to SNC-Lavalin in late 2010 and is expected to be operational in mid 2015.

The WAX consists of a new 335 MW powerhouse including two new Francis turbine units, each generating approximately 167 MW. The powerhouse is located downstream of the existing Waneta Dam and will make use of excess water which would otherwise be spilled during the runoff season. Water will be funneled to the turbines through an intake structure and two 10.5 meter diameter, concrete lined penstock tunnels. A 10 km transmission line will connect the powerhouse to existing electrical grids.

RFK was subcontracted by the heavy civil contractor, ASL-JV, to excavate the two penstock tunnels and install the cast in place concrete liner. RFK is a joint venture partnership between J.S. Redpath Limited, an

underground mine contractor located in North Bay, Ontario, and Frontier-Kemper Constructors ULC, a heavy civil tunneling contractor based in Nova Scotia, Canada. Since the penstock tunnel excavation was planned using drill and blast methods with significant grade, +17%, the combined experience of these two contractors made perfect sense.

SITE SPECIFIC

With the project site being located along two major rivers environmental awareness was, and remains, a major consideration to all work. Protected species such as the White Sturgeon, Rubber Boa snake, and Yellow Belly Marmot reside in areas surrounding the project site. All site contractors were required to adhere to strict environmental regulations especially regarding the use of concrete, explosives, and mobile equipment. An onsite water treatment facility was set up to treat all construction and runoff water which came in contact with the site prior to discharge.

Another consideration during drilling and blasting were the owner's requirements of zero fly rock and limited

blast vibrations. A single lane highway bridge and an existing railroad bridge, constructed during the 1940s, were located approximately 300 meters from the project site and were monitored during every blast. Blast vibrations were also an important consideration since powerhouse, intake, and tunnel excavations all took place within 500 meters of the existing Waneta Dam. All blasting was closely monitored to ensure no negative effects on the dam, railroad and highway bridges. Blast vibrations were kept below 50 mm per second peak particle velocity.

ACCESS ADIT

In order to start the penstock tunnel excavation early, while powerhouse and intake excavations were underway, a smaller access adit tunnel was developed. The access adit was 6 meters wide x 6 meters tall, modified horseshoe in shape, and 135 meters long with a grade of -12%. Developing the access adit allowed RFK to excavate the penstock tunnels and remain off of the surface works critical path and out of the way of other site excavations. The access adit was also used for initial training for those workers not familiar with underground works. (See Figure 1. Tunnel plan and profile.)

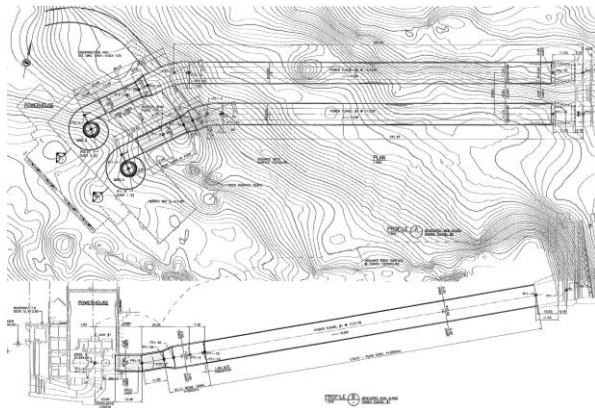


Figure 1. Tunnel plan and profile.

Four meter round lengths were drilled using a 2-boom Tamrock drill jumbo. A typical round consisted of 75 holes, 45 mm in diameter with three 100 mm diameter relief holes in the cut. Hole spacing was approximately 800 mm x 800 mm. Explosives used were packaged emulsion, "stick powder", with Nonel detonators. All blasts were initiated using electric blasting caps which were tied into detonating cord. Ground support in the access adit consisted a minimum 50 mm layer of 40 MPa, fiber reinforced, shotcrete followed by a typical 2 meter x 2 meter pattern of 2.4 meter long expandable (Swellex) type rock bolts. The access adit had low cover and would be used as primary ingress/egress during the tunnel excavation and the concrete liner phase. Eight steel arch sets were therefore installed at the portal on one meter centers to provide additional ground support. All utilities and ventilation were routed through the steel sets and down the access adit. RFK was able to complete the 135

meter long access adit in 40 days, working five days per week with two 10-hour shifts per day. (See Figure 2. Portal and Access Adit Development.)

PENSTOCK TUNNEL EXCAVATION

Two penstock tunnels were designed parallel, 10 meters apart, horseshoe in shape, and approximately 11 meters in diameter. After excavation a 300 mm thick cast in place concrete liner would be installed for hydraulic efficiency purposes only. Due to the large diameter of the penstock tunnels RFK determined the safest and most efficient excavation method would be top heading and bottom bench. Splitting the excavation into a separate top and bottom half allowed RFK to keep tight control over ground support and minimize the amount of open ground at one time. Another deciding factor was the availability of smaller mobile equipment.

Initial planning suggested using a split top heading where the top heading in each penstock tunnel would have two separate working faces side by side, one slightly ahead of the other, each approximately 5 meters wide x 5 meters tall. This method, similar to a pilot and slash, would have provided four working faces at any given time yielding greater flexibility in the excavation cycle.

Conversely, sequencing the excavation cycles between the four working faces would have required careful day to day planning and left little room for errors such as equipment breakdowns. Bottom bench excavation was always planned as full face using horizontal drilling and taken after top heading excavations were completed in each tunnel. (See Figure 3. Top heading and bottom bench excavation.)



Figure 2. Portal and access adit development.

As access adit excavation neared the intersection of the penstock tunnels RFK encountered better than expected ground conditions and determined that a full width top heading could be taken without compromising safety during the ground support cycle. Based on this information RFK chose to take a full face top heading, 11

meters wide by 5 meters tall, semicircle in shape. Doing so eliminated the flexibility of four separate working faces but allowed RFK to advance the entire top heading with one blast instead of two, making the operation more efficient overall.

Controlled blasting techniques were employed during top heading excavations to help define the excavation line and minimize overbreak in efforts to reduce the amount of concrete placed during the tunnel lining phase. Top heading drill patterns had approximately 98 blast holes with interior spacing averaging 800 mm x 800 mm. The perimeter of each round was line drilled with spacing averaging 450 mm and every other hole loaded during the blast. Four meter round lengths were drilled using the Tamrock 2-boom jumbo. Mucking was done using two CAT Elphinstone R1700G Load Haul Dump scoops, (LHD). Due to the wide top heading, 11 meters, RFK was able to use both LHDs to muck the face simultaneously, passing in the tunnel near the face. The use of two LHDs at once helped decrease the mucking cycle.



Figure 3. Top heading and bottom bench excavation.

From the access adit intersection power tunnel excavation was uphill at approximately 17% for 190 meters and downhill at approximately -15% for 20 meters in both tunnels. Blasted rock was taken to the downhill side of one power tunnel which was used as a muck bay. The downhill side of the adjacent tunnel was used as a sump. Blasted rock was hauled to surface using the LHDs after the heading was mucked out.

Initial temporary ground support, identical to that installed in the access adit, was installed in the penstock tunnels to allow RFK to continually advance the heading. All shotcrete was placed using a Normet Spraymec robotic shotcrete machine. Shotcrete was transported from surface using a single, 7 cubic meter, underground remix truck. Permanent ground support, consisting of 22 mm diameter x 4 meter long, fully grouted rebar dowels

were installed non-critical path behind the working face. All permanent ground support was installed based on a prescription by the onsite geotechnical engineer. Five separate rock classifications were defined and evaluations carried out daily after each blast was taken. Ground support classifications ranged from spot dowels only (Class I) to 100 mm of fiber reinforced shotcrete and lattice girders (Class V). Ground conditions in the penstock tunnels were good enough that RFK was only required to install Class I and Class II ground support.

To ventilate the underground excavations RFK used a fully reversible suction system. Two 1.3 meter diameter, 200-hundred horsepower ventilation fans were located on surface adjacent to the portal entrance. Two separate steel ducts of the same diameter were connected to the fans and advanced through the access adit. Once at the access adit/penstock tunnel intersection, one steel duct would split off to each of the two separate tunnels. The steel ventilation duct always remained approximately 18 meters away from the working face in the penstock tunnels while a smaller 30 hp, 0.9 meter diameter booster fan was used to push fresh air directly toward the working face. The 30 hp booster fans were set up in each tunnel in a fixed location and used 0.9 meter flexible ducting, advanced with the heading. Average air flows in the penstock tunnels were approximately 5,500 cubic meters per minute. Other utilities such as compressed air and service water were carried in 100 mm diameter HDPE pipe hung along the walls of the tunnels. Electrical cables for tunnel lighting and equipment were carried on the opposite side of the tunnel as the compressed air and water lines.

RFK was able to excavate both top headings, 451 lineal meters total, in 139 days and completed the bottom benches in only 82 days.

Two disadvantages associated with the steep grade excavations were difficulty mucking uphill and increased exposure during ground support operations. RFK was able to mitigate the latter by using a remote shotcrete arm on the Normet Spraymec allowing an initial layer of shotcrete to be installed prior to bolting. Shotcrete accelerator was used to reduce cure times so bolts could be installed during the same shift. A mechanized bolting machine was used to install the expandable bolts minimizing exposure to the operators. Excavating and mucking uphill was technically more difficult for operators but the equipment used was designed for underground mines where steep grades are more common. The slope was hard on tires, but with careful operation standard equipment was used effectively without requiring modification.

One advantage of the steep grade was that a pump was not required during ground support, drilling, and loading cycles to keep the face dry.

CONCRETE LINER

A smooth concrete liner was specified to minimize head losses through the penstock tunnels. Initial plans were for a modified horseshoe, or D shaped, tunnel cross section with finished inside dimensions of 10 meters x 10 meters.

Prior to the start of excavation a change order was approved converting the finished tunnel shape to full round 10.5 meter finished diameter. With permanent ground support being installed during the excavation phase the liners would not be exposed to any ground loads. The maximum design load was thus the pressure differential caused by rapid dewatering. While the tunnels are in use, and full of water, the ground around them will become saturated with an equal hydrostatic pressure. In an emergency the intake gates could be closed and water would drain out of the tunnels in approximately 2 minutes. In this case of rapid dewatering the surrounding ground will maintain the full hydraulic head of up to 70 meters on the concrete liner until the pressure slowly dissipates through leakage. With this in mind the designers specified the use of 35MPa plain concrete to cast the 300 mm thick liner.

It is notable that no reinforcing bar or fiber was required in the final concrete liner. The tunnel excavations were fully supported before concrete placement, and in the circular shape plain concrete was able to meet the design requirements. Reinforcement could have been used to reduce shrinkage cracking of the liner, but minor cracking was actually preferred as it will allow drainage into the tunnel in the rapid dewatering condition. Construction joints similarly required no water stop or bonding agents which would hinder equalization of water pressures.

The design requirements did have restrictive finish specifications. The tunnel liner could not vary from line or grade by more than 12 mm or by dimension/shape by more than 0.5%. On the 10.5 meter diameter finished tunnel up to 52 mm of differential between the height and width were allowed. Liner finish quality had to meet the British Columbia Ministry of Transportation Class II requirements. This required all honeycombs over 25 mm diameter be filled, all bugholes over 5 mm diameter be pointed and the surface given a rubbed finish where more than 50 such voids occurred per square meter. Surface irregularities 3 mm high were allowed with restrictions on their size and number.

TUNNEL FORM DESIGN AND FABRICATION

In order to keep tunnel concrete works off the overall project's critical path RFK requested proposals from seven different suppliers for a self advancing concrete form which would allow a full pour cycle every 24 hours, safely operate on a 17% slope, and be able to meet the specified finish requirements. Ceresola Tunnel Lining Systems (CTLS) of Switzerland (now Max Bögl) was the chosen supplier and undertook the design and fabrication of a walking beam style steel form. It was agreed the form would be able to cast a 7.5 meter long full round section of the tunnel liner, walk itself through the tunnel on its own carrier, and be designed to operate on a 17% slope. The form used by RFK on this project is the largest full round form CTLS had constructed to date.

Since the tunnel form was only 7.5 meters long internal supports "spud pins" were not required. To prevent movement during concrete placement the front of

the form was braced against the surrounding rock and the rear against the previous concrete pour by six large screw jacks on each end. Two screw jacks in the crown, one on each side, and two in the invert. In an effort to reduce cycle times a steel framed, cantilever bulkhead system was developed which would fasten to the upstream leading edge of the steel formwork, eliminating the need to brace the bulkhead against the rock. In surface trials the provided cantilever bulkhead system proved difficult to fit around other installations on the end of the form such as walkways and hydraulic cylinders. The individual parts were also too heavy to efficiently assemble by hand on a daily basis. RFK decided to use rough cut 2x8 bulkhead material and support it using traditional wood 2x4 walers and stiff-backs. The wood supports were not designed to withstand concrete loads in cantilever so they were pinned and braced to the perimeter rock using 20 mm steel dowels.

Advancement was accomplished by designing the round form and the carrier to walk itself. Rollers were installed on the carrier beams to allow the form to slide back and forth with the carrier resting on the ground. The same rollers could be used to move the carrier when supported by the form. Not having wheels on the ground meant the form could be walked over mildly uneven surfaces, did not require a rail system, and was stable in the sloped tunnel. The form could also be walked sideways by means of side adjustment cylinders.

The tunnel form was fabricated and structural elements assembled for testing and inspection in Seveso, Italy. After workshop inspection the form was disassembled and loaded into 11 standard 40 foot shipping containers for transport to Trail, BC. On arrival the 15 full form elements (1.5 meter x 7.5 meter x 1.6 meter up to 4200 kg each), 10 half elements for the invert, handrails, and miscellaneous parts were skidded out of the shipping containers at a storage yard approximately 7 km from the project site. Each element was then individually transported to the assembly location at the project site as needed. (See Figure 4. Tunnel form inspection.)



Figure 4. Tunnel form inspection.

TUNNEL FORM ASSEMBLY

On site the assembly location was on the surface near the head pond and adjacent to the 40 meter deep intake excavation. The carrier itself was assembled then the five elements comprising the crown were bolted together. The crown was lifted as one unit and attached to the carrier. The side elements, or wings, were bolted together and hung from the crown while the invert was assembled in place under the carrier. After the major elements were bolted together the electrical, hydraulic, pneumatic, communications and water systems were installed. Overall, surface assembly took 11 weeks. Once assembled, the form was tested and modifications were made as needed before walking the form under its own power to the edge of the intake.

A location for the shortest lift crane radius (15 meters) into the intake was cleared and leveled for placement of a 275 US ton lattice boom crawler crane. This gave a load limit of 48,000 kg at the self-imposed 75% capacity to avoid the restrictions of a Critical Lift. Fully assembled the form weighed approximately 135,000 kg. (See Figure 5. Tunnel form re-assembly in bottom of intake excavation.)



Figure 5. Tunnel form re-assembly in bottom of intake excavation.

The form elements, placer car, and feet were removed to allow the carrier to be lifted and set in the

bottom of the shaft. The invert, carrier, crown and sides, each containing all installed utilities and sub-assemblies, were then hoisted to the bottom of the intake, in order. Each part was directly attached to the elements already in place, reattaching the invert last.

After full reassembly the form was shifted 20 meters sideways using 200 mm side adjustment cylinders and aligned with Tunnel 2. The form was then walked, as intended, to the downstream starting station of Tunnel 2 over the course of approximately one week. Although designed for the slope, a large moment was inflicted on the system as it was walked down the tunnel. When the carrier was raised and extended forward down the tunnel two screw jack feet on the lower end supported the majority of the system's weight; along with a moment from the extended carrier. An anchor pin assembly was provided on the upper end of the form to arrest longitudinal forces, but it was difficult to prevent load transfer to the vertical supports. Extreme care was required while walking downhill to prevent damage to the screw jacks. Advancing the form back up the tunnel did not have the same challenges. The carrier was advanced and set in place while the form was still enclosed in the previous pour's concrete. The tight encasement prevented any movement with loads being distributed into the concrete.

Adjustments had to be made after the first two pours to account for the rear of the form and carrier advancing into the poured liner. After the third pour a cycle was defined, although not close to the 24 hour target. A cycle consisted of fixing the form in place, building the bulkhead, pouring concrete, curing the concrete, stripping the bulkhead, advancing the carrier, advancing the form, cleaning, oiling, and aligning the form for the next pour. After 10 pours the overall cycle was typically 48 hours (4 shifts). Of the 48 hour cycle, concrete placement took only 7 hours. The following shift stripped the bulkhead and moved the carrier forward. On the second day the form was advanced and reset. Night shift then started a new bulkhead and set up for the next pour. By the 15th pour the cycle had been reduced to 36 hours.

Several concrete mixes were submitted for approval to allow flexibility based on weather conditions and temperatures. Because placement happened during the spring and summer months a mix design with the highest water/cement ratio (0.42) and highest fly ash content (22%) was used. RFK determined this mix could be accelerated as needed to keep up with the pour schedule. Tight controls were necessary to ensure the concrete would perform as designed. Stripping strength of 4 MPa had to be reachable within 12 hours. Accelerator (typically 181ml/100kg cementitious) was added on site no more than 30 minutes prior to start of discharge. A minimum 180 mm slump was needed because of the limited access behind the form to place and vibrate. At 220 mm slump the concrete mix was too wet and began to segregate. The steep grade and use of high slump concrete helped to ensure all surface irregularities from the blasted rock were filled.

A Maturity Meter was used to monitor temperature production and rate of hydration of the placed concrete to allow stripping as soon as the concrete reached strength.

Trial batches defined the rate of compressive strength gain to the Time Temperature Factor (TTF) output of the meter. When the TTF read 350 the bulkhead could be safely stripped (2 MPa), as soon as it read 450 the concrete was self-supporting and the steel form could be advanced (4 MPa).

LOOKING AHEAD

Formation of flat, elongated bug holes in the concrete below spring line of the finished liner has been a problem since the first pour. The wide radius of the tunnel with a nearly flat invert has tended to trap air and water bubbles against the steel. Bubbles have seemed to move vertically through the concrete until they hit the surface of the form. The shallow angle then prevents them from sliding along the form to escape the pour. Of the first 15 pours all require the full rubbed surface below spring line.

Efforts to improve the finished concrete surface will include monitoring and fine tuning placement procedures, testing various form release agents, and minor adjustments to the mix design. Variables associated with placement include injection ports, which ones and how often they are switched; and vibrator use sequence and duration. Form release agents have been, and will continue to be, tested to see if a water based product can be found to further reduce bug holes (oil based form release agents will not be used as any residue on the form or the fresh concrete is quite slippery). Adjustments to the concrete mix design primarily include changes to the slump and workability admixtures of the concrete.

The second major area for improvement is to reduce the overall cycle time. It is difficult to say if the 24 hour cycle can be achieved. Assuming an optimistic 6 hour pumping time, and 10 hours to reach 4 MPa; 8 hours are left to strip, clean and advance the form as well as start the bulkhead. This is a very optimistic schedule that may or may not be achieved. Regardless of the cycle time the form has proved to operate effectively on the slope and produce a smooth round concrete surface. Very little remedial finish work beyond the patching of bug holes will be required in any area. (See Figure 6. Finished concrete liner.)



Figure 6. Finished concrete liner.