Design and Construction of Unlined Water Tunnels – an Update

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ABSTRACT
Many papers were written on the design and construction of unlined water tunnels 30 to 50 years ago, however, there are relatively few recent references on the subject. This paper presents an update based on experience on many recent water tunnels for hydro and water resources projects.

There is a wide range of approaches that owners and engineers currently use to the design of water tunnels, nationally and internationally. This paper discusses the current state of the practice in the Western Canada, recent experiences and recommendations for safety, rock support, corrosion protection, erosion protection, types of lining, hydraulic fracture avoidance, invert treatment, and tunnel inspection for unlined water tunnels. The paper does not attempt to cover the tunnel lining or construction practices for squeezing, swelling slaking or other mineral deterioration conditions as each of these is a major topic and worthy of separate publications. The paper focusses on the design and construction of recent water conveyance and pressure tunnels in rock which are mainly unlined.

1 INTRODUCTION

After a boom in the construction of hydropower projects in the middle half of the last century, hydropower, and especially dams, went out of favour in the 1980s and 1990s. In this period, the industry lost significant experience and expertise in the technology as hydro personnel changed focus to other types of work or retired. In the early 2000s the world woke up to the realization that hydropower is the only traditional energy source that does not significantly contribute to climate change. Since then there have been a significant number of hydropower projects built around the world, particularly in Canada, South America and Southeast Asia. Many of these recent projects have been developed by independent power companies who sell the power to national power utilities. This has resulted in the construction of many new hydropower projects, especially run-of-river projects, involving unlined tunnels.

Many of the recent independent power developers/owners have power sales contracts or water licenses that expire after 40 or 50 years. After that, the project reverts to the state/provincial utility or to some government or First Nations authority. Consequently, the developers, who are particularly interested in saving up-front costs (i.e. construction costs), have only required the projects to have a 40 or 50 year design life. However, as with most hydropower projects, these projects will still be providing low cost power in more than 100 years’ time.

With this climate of project development and the recent advances in tunnelling technology, there have been several changes to the design approach to power tunnels. Some of these are for the better and some are short-sighted. This paper outlines some of these changes in an attempt to promote discussion and build consensus in the tunnelling industry for future projects.

Rock support, tunnel lining and construction practices for squeezing, swelling slaking or other mineral deterioration conditions are not covered in this paper as each of these major issues has been covered in many recent technical papers.

This paper focusses on unlined hydropower tunnels in rock. Most of these projects are in steep terrain where the excavations have been by drill-and-blast, although there have been many power tunnels excavated by TBM. The issues described below apply equally to drill-and-blast tunnels as to TBM tunnels.

2 SAFETY IN UNLINED TUNNELS

Most existing water tunnels in hard rock are “bald” i.e. they have no support, except in local areas of poorer rock and in areas where leakage would be a problem. However, Australia and Europe have recently implemented laws that do not allow personnel to enter under “unsupported roof” at any time. This was introduced from the mining industry where the injury rate from rockfalls has apparently dropped significantly since the introduction of these laws. Canada and the USA do not (yet) have similar laws but many contractors and owners are adopting this policy.

This requirement means that safety support has to be installed after each round or tunnel advance. However, there is no clear definition or universally accepted criteria for what constitutes adequate for safety support for personnel entry. Recent projects have seen the use of springline to springline support by pattern rock bolts, pinned wire mesh, fiber reinforced shotcrete or combinations of these support measures. In reality, none of these support measures is suitable for all conditions that can be expected in any tunnel and the decision on the type of support for personnel safety should be left to the contractor’s supervisor at the tunnel heading.

If wire mesh is installed for worker safety, the question arises as to whether it should be left in place at the end of construction. In a low corrosive environment, the mesh and mesh pins may last up to 40 or 50 years – but most hydro projects will be in operation for 100 years or more. The consequence would probably be catastrophic if mesh detaches and “balls-up” in the tunnel or is carried downstream into the valves or turbines.
Suggested criteria for safety support for future tunnel construction are as follows:

- Chain link mesh or welded wire mesh supported by mesh pins is only suitable for holding up small blocks of rock but should not be used to support large blocks of rock or potentially large rockfalls unless it is used in conjunction with rock bolts, and shotcrete with lattice girders or steel sets.
- Shotcrete should be reinforced with fibers or welded wire mesh. It should be at least 50 mm thick. Chain link mesh should not be used as reinforcing for shotcrete as the shotcrete cannot adequately penetrate through the mesh.
- Geosynthetic geogrid mesh (such as UX3326 by Tensar) is light and can be used as an alternative to chain link mesh. It has similar strength to chain link mesh, is easier to install and is more easily removed. As with chain link mesh, it cannot support large rockfalls without rock bolts or steel sets.
- Pattern rock bolts without mesh are only suitable in rock with large block sizes and widely spaced joints.

All types of safety mesh should be removed from water tunnels at the end of construction. However, this leaves the residual problem of whether it is safe to inspect existing tunnels without entering under “unsupported roof”. This problem may become moot in future as remotely operated vehicles (ROVs) become more widely used to inspect tunnels.

3 TYPES OF ROCK SUPPORT

In most unlined water tunnels, the primary rock support is usually provided by rock bolts with reinforced shotcrete (using lattice girders, welded wire mesh or fibers) where the joints are closely spaced or the rock is erodible or will degrade over time.

Epoxied resin grouted rock bolts were popular in the tunnelling industry from about the 1970s, however, recent research and experience has shown that they do not provide reliable long term corrosion protection for several reasons (Gates 2013): (1) they require close quality control for every bolt installation i.e. number of cartridges, number of rotations, and hole length, (2) the plastic sheath often wraps around the bar and prevents full grout encapsulation, (3) the epoxy resin tends to crack as it get old, (4) the resin does not offer chemical corrosion protection as cement grout does, (5) the resin and bar have to be at the recommended temperatures during installation, and (6) the end of the bar at the collar often does not get grouted as this requires the hole and the underside of the face plate to be filled with resin and when some of the resin then drips out of the hole it is messy so miners tend to use fewer cartridges than required. However, many contractors prefer resin grouted rock bolts as they are quick to install — and cheap.

Recent research and experience has also shown that any form of single corrosion protection for rock bolts cannot be relied upon for a 100-year design life so double corrosion protected, mechanically anchored, cement grouted rock bolts are now more widely accepted as the only type of rock bolt that can provide permanent rock support in water tunnels.

4 TUNNEL LINING REQUIREMENTS

A concise summary of the decisions required for selecting the lining for pressure tunnels is provided in Figure 1 (Merritt, 1999). This reference provides recommendations of where and what type lining is required for each type of rock, internal pressure, ground cover and ground water level. For good quality, strong, non-soluble, low permeability rock where the internal water pressure is less than the minimum in-situ rock stress no lining or lining with no reinforcement is required. These are the conditions in most lengths of unlined hydropower tunnels.

![Figure 1. Power Tunnel Lining Selection (from Merritt 1999)](image)

The “Merritt chart” (Figure 1) does not address scour in pressure tunnels, however, flow velocities in power tunnels are typically low – between 2 and 5 m/sec. Unless the rock is particularly weak, these velocities are too low to cause scour, so water tunnels in good quality rock need only be lined in the following areas and/or conditions:

- At the downstream end of the tunnel where in-situ rock stresses are lower than the internal water pressure (as discussed below);
- Where rock minerals degrade and could cause tunnel collapse; and
- Where the rock has the potential to swell.

Hydraulic and structural engineers often favour concrete lining to reduce hydraulic losses. However, for the same hydraulic losses along a water tunnel, a tunnel can be lined with concrete or made slightly larger and left unlined or shotcrete lined. It is significantly more cost effective to excavate the tunnel to be slightly larger and leave it unlined, or partially shotcrete lined, than to line the tunnel with concrete. In addition, shotcrete lining can be applied (where required) during tunnel excavation whereas concrete lining cannot start until tunnel excavation is complete so there are significant schedule advantages to using shotcrete.

In addition, there have been significant advances in shotcrete technology in the last decades to a point where a thick shotcrete lining can applied in a single pass and
shotcrete can have greater strength than traditional concrete lining.

The potential for scour is greater in diversion tunnels where velocities are significantly higher than in power tunnels. The most practical method of assessing scour potential is the Erodibility Index Method (Annandale 2005) which is summarized in Figure 2. The Erodibility Index is an measure of the erodibility of the rock mass which uses parameters similar to the “Q method” of rock mass classification. This is plotted on Figure 2 against Stream Power, or the hydraulic scour forces applied to the rock. Where the rock and hydraulic conditions in a tunnel plot above the dashed threshold line in Figure 2, scour is predicted and tunnel lining is required. Where the conditions plot below the threshold line, then no lining is required.

![Figure 2. Erodibility Index Method for Assessing Rock Scour (from Annandale 2005)](image)

The diversion tunnels of several recent dam and hydropower projects have no lining or just shotcrete protection on erodible zones or seams. These have performed well and have withstood flow velocities greater than 15 m/sec (Humphries and Hoek 1987, and Humphries et. al. 2005).

5 HYDRAULIC FRACTURE/HYDRAULIC JACKING

The concept of hydraulic fracture in pressure tunnels is now widely understood. For preliminary designs, the 1971 “Norwegian Criterion” (Bergh-Cristensen 1971 and Figure 3), combined with subsequent refinements, can be used to estimate the length of the steel lining. However, this criterion was developed for typical geologic conditions in Norway and it should not be used for final design of the length of the steel lining because different rock stress conditions are often encountered in different geologic conditions. Recent hydrojacking tests at several hydropower projects in British Columbia have shown that the Norwegian Criterion significantly overestimated the minimum in-situ rock stress so the steel lining had to be lengthened during the final design phase of the projects.

Consequently, for the length of the steel lining for final design of a pressure tunnel, in situ hydrojacking tests to measure the minimum in-situ rock stresses are strongly recommended. These hydraulic jacking tests can be done in boreholes drilled from the surface or from holes drilled from within the tunnel during tunnel excavation.

![Figure 3. “Norwegian Criterion” for Estimating the Required Length of Steel lining in Pressure Tunnels (from Bergh-Cristensen and Dannevig 1971)](image)

6 TUNNEL INVERT TREATMENT

There is also no consistency on the issue of invert treatment in unlined water tunnels. The issues are:

- In most older unlined tunnels, the invert was covered with a concrete slab;
- In a drill-and-blast tunnel, the “lifter holes” are coarsely drilled and heavily charged so the rock profile of the tunnel invert is usually very irregular, as shown in Photographs 1 and 2;
- If all tunnel muck is removed from the invert of the tunnel the surface becomes impassable for construction equipment. In one tunnel in Canada where the tunnel invert had been cleaned to rock, repairs were required after some years in service so it was necessary to bring in crushed rock to create a running surface and then remove the crushed rock after the repairs were completed;
- Removing all the tunnel muck from the invert of a tunnel can be very time consuming and expensive unless the tunnel has a steep gradient;
- The flow velocities in water tunnels are typically low and would not erode the rock or tunnel muck if it were not removed from the invert, however, the easiest and quickest way to fill a tunnel (or refill it after a shut-down) is to open the intake gate which would flush a lot of muck downstream.

Consequently, the best approach appears to be to place a relatively thin (150 mm typically) concrete invert slab on top of the tunnel muck. The slab need only be lightly reinforced but it must have drain holes to prevent uplift during dewatering. The slab can be placed directly on compacted tunnel muck as long as the muck is comprised of hard, compacted particles that will not break down.
TUNNEL INSPECTIONS

Traditionally, power tunnels were dewatered and inspected every few years. More recently, the industry has moved away from this practice as the dewatering process has been found to cause rockfalls. However, some contracts (particularly design-build, DBO, and BOOT contracts) require the tunnel to be inspected after a few years in service.

To limit the potential for rockfalls during dewatering, the pressure drop in unlined tunnels is typically limited to less than 5 m/hour.

As discussed previously, remotely operated vehicles (ROVs) have become very efficient and cost effective and are likely to become the industry standard for tunnel inspections. This will avoid the problems of personnel entry into areas of “unsupported roof” for inspections but the personnel access issue would have to be addressed carefully if repairs are required.

8 SUMMARY AND RECOMMENDATIONS

There is a wide range of current practice relating to the design of unlined water tunnels. This paper is intended to generate discussion in the tunnelling industry on several of these issues. The following recommendations summarize the author’s personal experience from recent water tunnel projects. They should not be regarded as accepted tunnel industry practice and are not suitable for all unlined water tunnels. The author’s recommendations are as follows:

- Personnel should not be allowed to work under unsupported ground except in special circumstances;
- Double corrosion protected, cement grouted rock bolts should be used in all long-life water tunnels;
- If shotcrete is required for support or protection of the rock, then it should be fiber reinforced or reinforced with 150mm x 150mm non-galvanized welded wire mesh. Chain link mesh should not be used as reinforcing for shotcrete;
- For personnel protection during construction, chain link mesh, welded wire mesh or geosynthetic mesh with mesh pins should only be used if the rock blocks and the volume of potential rockfalls are small. Rock bolts or lattice girders and shotcrete are required to support larger blocks;
- Mesh used for personnel protection during construction of power tunnels should be removed before the tunnel is put into service;
- The “Norwegian Criterion” should not be relied upon for final design of the length of the steel lining at the downstream end of pressure tunnels. Hydraulic jacking tests should be done at tunnel level to measure the minimum in-situ rock stress and determine the length of the steel lining;
- The Erodibility Index Method provides a good estimate of the potential for rock scour and the requirement for tunnel lining in a water tunnel;
- For long term inspections and maintenance of a tunnel, a thin, reinforced concrete invert slab is recommended for inspections and maintenance;
- The design of future water tunnels should provide facilities for an ROV to be used for routine tunnel inspections; and
- Water tunnels should not be dewatered for routine inspections unless there is a known problem.

REFERENCES


