Complex tunnelling at the Chimney Hollow dam

A. Wilkes and G. Raines, WaterPower & Dams (Stantec), USA

The Chimney Hollow reservoir project is a new planned scheme approximately 13 km west of Loveland, Colorado. The Municipal Subdistrict of the Northern Colorado Water Conservancy District is developing the project as a component of the Windy Gap Firming project. Stantec was awarded the engineering services contract for the project in early 2016, which includes a main dam, spillway, saddle dam, and conveyance features connecting the Chimney Hollow reservoir to the existing Colorado-Big Thompson project infrastructure.

The Chimney Hollow reservoir project involves a number of interested parties: the Municipal Subdistrict, and others including the Northern Colorado Water Conservancy District, a public agency that has been created to build and operate the Colorado Big Thompson (C-BT) project jointly with the US Bureau of Reclamation. Conveyance from the new reservoir to the existing C-BT infrastructure required tunnelling, and an inlet/outlet (I/O) tunnel was selected as part of the 'alternatives analysis' undertaken in early 2017. The works consist of an I/O structure, an upstream tunnel and grout chamber with backfilled steel pipe final lining, a valve chamber containing critical flow controls with a cast-in-place concrete final lining, and a downstream tunnel where the I/O conduit is supported on saddles within a cast-in-place concrete final lining.

Combatting water supply shortages

The C-BT project collects water from the upper Colorado river basin on the western slope of the Rocky Mountains and conveys it beneath the Continental Divide to provide water and hydropower to northeast Colorado. The Municipal Subdistrict is a separate and independent conservancy district formed to plan, finance, build, and operate the Windy Gap project. The additional storage provided by the Chimney Hollow reservoir, contemplated since the Windy Gap project's inception, will provide more reliable Windy Gap water deliveries. This is crucial when considering that the Subdistrict estimated that its communities could have a water supply shortage of 78.9×10^6 m^3, or approximately 109.77×10^9 l, by 2030.

An innovative approach to dam safety initiatives

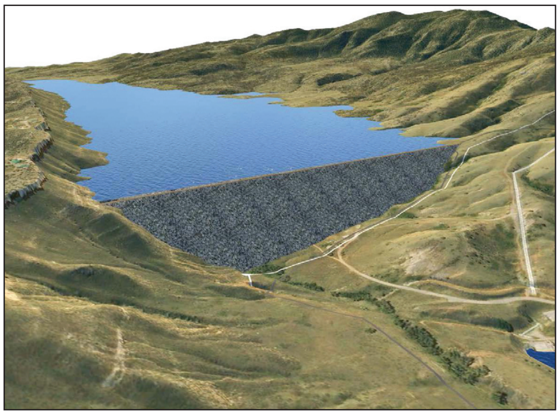
In addition to the growing population on the Front Range mountains, much of the work that will be done at Chimney Hollow was driven by a larger trend of dam safety initiatives in the USA. As a result of potential hazards associated with the storage of water in reservoirs, the western USA has some of the most stringent laws governing dams. These potential hazards are addressed through state dam safety programmes that strive to improve dam condition and safety. Dam safety at Chimney Hollow was of paramount concern to Stantec, the client, the State dam safety regulators, and the review boards, and rightfully so. When constructed, the main dam will be the highest dam constructed in Colorado in 50 years and is one of the first asphalt core rockfill dams (ACRD) in the USA. The planned reservoir will provide 37×10^6 m^3 firm yield to the project's participants. The grouting programme and valve chamber components of the I/O works in particular were driven and designed around dam safety priorities.

Adapting to unconventional lining requirements

One of the most challenging aspects of the project was the final lining and valve chamber design. The I/O works design requires an open access tunnel from the valve chamber to the downstream portal. Instead of continuing the upstream tunnel construction downstream of the grout curtain, the design specifies a cast-in-place final lining to allow the client access to the critical electrical and mechanical equipment housed in the valve chamber to detect leaks, defects, and perform maintenance.

To protect this equipment from water infiltrating the final lining, the valve chamber was designed to be watertight through the use of a PVC membrane to be installed outside of the concrete final lining. This membrane is only installed around the valve chamber and not for the entire tunnel. The membrane will be connected to a seepage ring welded to the I/O conduit where it penetrates the bulkhead wall at the upstream end of the valve chamber. This bulkhead wall separates the valve chamber from the concrete backfilled grout chamber and the upstream tunnel. An expansion joint filled with compressible joint filler has been provided between the bulkhead wall and the I/O conduit to allow for movement and differential settlement between the valve chamber and the grouting chamber.

The valve chamber in particular has very high loads acting on the final lining from two sources. The dam embankment will be placed on the rock mass of the right abutment through which the tunnel will run. As the valve chamber is near the dam axis and the maximum dam height, it experiences some of the highest surcharge loading. In addition to this surcharge load, very high hydrostatic loading conditions have been estimated to act on the lining, as discussed below, from the full reservoir.



Artist's impression of the Chimney Hollow site.

The surcharge loading condition was modelled in the finite element modelling program RocScience RS2. Plane strain models were developed for different locations along the tunnel alignment which reflected the sloping ground surface of the right abutment accurately and then placed the dam embankment constructed at that location. The location of the tunnel alignment places the centre of the tunnel alignment underneath the dam, with the sloping dam embankment reducing the surcharge loading conditions as it nears the portals at either ends. Approximately the last 90 m of the downstream end and the first 243 m of the alignment experience little to no surcharge loading, as they are outside the footprint of the dam. RocScience Unwedge was used to model the joints and discontinuities within the rock mass to develop point and area loads, which were then input into the RS2 model along with the hydrostatic loading conditions.

The existing groundwater levels along the tunnel alignment vary from 5 to 15 m above the crown of the tunnel and, although mostly influenced by the nearby Carter Lake reservoir, vary seasonally. Once the reservoir has been filled to capacity, it is estimated that the groundwater pressure will increase and be the highest upstream of the grout curtain, and then decrease as the tunnel travels downstream. The upstream tunnel is located upstream of the dam foundation curtain grouting and is therefore designed for the full potential hydrostatic force of 91 m of water head possible from a full reservoir condition. Hydrogeologic modelling was performed to calculate the groundwater pressures downstream of the grout curtain with a full reservoir condition. This pressure head profile was used to design the valve chamber and the downstream tunnel's final lining. The valve chamber is designed for 45 m of hydrostatic pressure head, while the downstream tunnel is designed for pressures ranging from 40 to 21 m of head, decreasing in the downstream direction.

The original conceptual design of the tunnel initially had the entire alignment as a Roman arch or horseshoe cross section. However, once analysis and design of the final lining began, it was determined that the high embankment surcharge loads and the high hydrostatic loads acting on the lining developed extremely high stress concentrations and shear forces at the haunches of the tunnel. It was then decided that the valve chamber and the upstream reach of the downstream tunnel would be best designed with a circular cross section, to handle the high loading conditions as economically as possible. Following construction of the circular final lining, a semi-circular shaped levelling slab will be placed in the invert of the circular tunnel to provide a surface for installing the I/O conduit on pedestals and for maintenance access.

The Chimney Hollow reservoir will be connected to the existing Colorado-Big Thompson project infrastructure.

Applying multiple conventional grouting techniques

The challenging grouting design took many forms based on the project and dam safety requirements. Six types of grouting are to be performed along the approximately 610 m I/O tunnel, including contact grouting, skin grouting, modified contact grouting, consolidation grouting, curtain grouting, and water control grouting. These techniques are widely accepted and used on many projects worldwide, but it is rare that you find all of them used for a single tunnel. The driver for this complex grouting programme is dam safety, as the combination of these techniques is intended to create a treated zone around the I/O tunnel to mitigate risks associated with the tunnel beneath the abutment of the Chimney Hollow dam. Each type of grouting serves a unique purpose, and the combination of them all is a well orchestrated design solution that prioritizes dam safety.

One of the most important grouting methods designed for the I/O tunnel is the curtain grouting performed underground. The primary purpose of curtain grouting in reservoir construction is to reduce the permeability of the grouted zone and reduce seepage beneath the dam. Curtain grouting from the surface will be performed prior to the tunnel excavation. As the tunnel is excavated, the curtain will be disturbed by excavation techniques (such as blasting) and so must be repaired to function properly. The curtain grouting performed from within the tunnel will be started once the tunnel has been driven and the temporary ground support installed. Grouting operations will occur within a grout chamber, which is a 2.7 m-high by 4.3 m-wide excavation between the upstream tunnel and valve chamber designed to accommodate grouting equipment. To provide adequate grout coverage, the curtain grouting will extend approximately 3 m from the grout chamber excavation.

Consolidation grouting is required at thrust blocks within the downstream tunnel and around the valve chamber. For the portion of the conduit that is supported on concrete pedestals within the downstream tunnel, there are two alignment changes that require thrust blocks to support the hydraulic thrust loads from the pipe and to limit pipe movement. Both of these thrust blocks bear on the rock mass and generate a substantial thrust force. Structural consolidation grouting will be done at both locations so that the rock mass provides the desired bearing capacity for the design thrust force and to improve the bedrock's competency and stiffness. Consolidation grouting is also designed around the valve chamber to aid in the performance of the PVC waterproofing membrane.

Modified contact grouting is the flagship grouting method applied in the design of the I/O tunnel. This technique is a modified version of traditional contact grouting of the void between the cast-in-place concrete final lining and the rock mass. The goal of modified contact grouting is to obtain a hydraulic cutoff and prevent water from migrating longitudinally along the tunnel alignment.

Much like traditional contact and skin grouting techniques, the hydraulic cutoff that modified contact grouting creates is integral to dam safety. Developed by the Stantec tunnel design team in Atlanta, this technique has been successfully performed on multiple projects in the area. Modified contact grouting involves contact grouting at higher pressures with a less viscous grout mix to force the grout further into the rock mass and permeate throughout fractures and bedding planes around the perimeter of the tunnel. In addition, all panning and drain pipes are filled with grout to seal potential flow paths along the tunnel alignment. The blending of contact grouting and consolidation grouting methods achieves the same results as each method individually. But performing modified contact grouting instead of individually performing the two separate techniques benefits both project schedule and cost.

Responding to a rigorous review process

The Stantec tunnelling team encountered one final opportunity during design. In addition to the robust project requirements, the project went through an extensive review process, from both Stantec's own internal review board as well as an external project review board sponsored by the client. After more than a year of design and review iterations, the final design was submitted to the client for bid. The completed tunnel design package is a culmination of a multidisciplinary effort accomplished by the Stantec tunnel design team that came together across many offices to tackle strict safety project requirements while also incorporating innovative techniques. Team members for the tunnel alone worked from San Diego, Tempe, Bellevue and Denver on the design.

Coordination with the dam design criteria and multiple project review boards resulted in dam design constraints that were not always congruent with the design constraints of the tunnel. Thus, the tunnel design was affected and modified based on requirements for the dam design that produced a more conservative design than has been used on other reservoir projects. In addition, the owner integrated an extensive review process into the final design of the project, including internal Stantec review meetings as well as external review facilitated by the owner. Furthermore, to assure dam safety concerns were addressed, the external reviews included input from regulatory agencies and dam design veterans.

The relationship between the dam and tunnel design is evidenced by the four different cross sections along the tunnel length. Dam safety concerns required that the I/O conduit had a valve chamber beneath the centreline of the main dam. The valve chamber allows the operators to cut off flow directly beneath the dam, remove reservoir head from the downstream conduit, and provides operational flexibility to have valves in both the valve chamber and valve house that control flow to and from the reservoir. In addition, the design alternative adopted keeps the conduit accessible for inspection, and provides access to the valve chamber from the downstream portal. This necessitated the inclusion of the open, concrete-lined valve chamber and downstream tunnel. Similarly, the grout chamber was required as part of the dam design to complete the curtain grouting within the vicinity of the tunnel. If not for these dam safety requirements, the full tunnel length would likely have been completed using the upstream tunnel design, as is typical for water conveyance tunnels beneath embankment dams.

During dam construction, the I/O tunnel is intended to be used as a diversion for surface water in the Chimney Hollow Valley. The purpose of the diversion is to direct surface water collected within the Chimney Hollow watershed away from the dam foundation. Maintaining proper foundation conditions is critical during dam construction, and the flows must be redirected to protect features under construction. Because the tunnel was needed to provide diversion it had to be constructed prior to rockfill placement. Timely tunnel construction is a critical path for dam construction so that the diversion is in place.

The multiple reviews allowed dam safety concerns to be communicated effectively to the tunnel design team and helped convey the importance of changes to the tunnel throughout the design process.

Delivering the final design

The final design of the Chimney Hollow reservoir project represents an innovative approach to dam, tunnel, and conveyance design. The results of the multiple review boards allowed Stantec and the Municipal Subdistrict to develop a design that prioritizes dam safety and successfully achieves all project goals.

As the final design documents are stamped and prepared for construction, both Stantec and the Subdistrict are eager to see the many design elements come to fruition. For the project team members that live in Colorado, the construction of this reservoir means having a more reliable water supply in the years to come that can adapt to the ever-changing climate and population growth. The completed reservoir will also be a new recreation area and bring communities together across the northern Front Range. ◊

A. Wilkes

G. Raines

Austin Wilkes has almost five years of experience as a geological engineer and designed the initial support for the inlet/outlet works tunnel, among other tunnelling duties. He has a strong knowledge of geological and geotechnical engineering principles and is experienced in site investigation, geologic mapping, design calculations and modelling, construction oversight, report preparation, and design package development.

Stantec, 1560 Broadway, Suite 1800, Denver CO, 80223, USA.

Gregory Raines has more than 30 years of experience in tunnel planning, design, and construction and was the lead tunnel engineer for Stantec at the Chimney Hollow dam project. He has consulted on hundreds of tunnelling projects, which include tunnel inspection/rehabilitation, large diameter water/wastewater tunnels, mining-related tunnels, deep shafts, and caverns.

Stantec, 9665 Granite Ridge Dr., Suite 220, San Diego, CA 92123, USA.