REHABILITATION OF THE OUTLET WORKS AT THE TAUM SAUK PUMPED STORAGE PLANT

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ABSTRACT

The Taum Sauk Pumped Storage Plant, which originally began operation in 1963, had a catastrophic failure of the upper reservoir in 2005. During the construction of the new upper reservoir dam, the entire outlet works consisting of a 137 meter (m) (450-foot (ft)) deep shaft and over 1830 m (6,000 ft) of lined and unlined tunnels, were inspected and rehabilitated. This paper discusses the inspection program, design and options analysis for rehabilitation, and the construction including safety and access issues. Rehabilitation included replacing sections of the steel liner, reinforcements to the unlined sections, and grouting and shotcrete patching.

INTRODUCTION

The Taum Sauk Project consists of an upper reservoir and a lower reservoir connected by a vertical shaft, rock tunnel, and penstock as shown in Figure 1. The powerhouse has two pump-turbines with a total generation capacity of 450MW. The original rockfill dike, constructed in 1963 to form the upper reservoir at the Taum Sauk Pump Storage Project, failed abruptly on December 14, 2005. The original upper reservoir dam was removed and completely rebuilt as a 2.17 million cubic meter (2.83 million cubic yard) Roller Compacted Concrete (RCC) dam in compliance with Federal Energy Regulatory Commission (FERC) Regulations and Missouri environmental permitting regulations. Ameren, the owner of the Taum Sauk Project, has reconstructed the upper reservoir of the facility to restore the original storage capacity, and is operating the reservoir according to the current project license.

FIGURE 1: TAUM SAUK SCHEMATIC
During the reconstruction of the upper reservoir, Paul C. Rizzo Associates, Inc. (Rizzo), in cooperation with Ameren, performed an inspection of the outlet works. The results of this inspection were used to develop a rehabilitation program for the outlet works. This paper describes the inspection, the design and options analysis, and the construction process including safety, access, and the difficulties encountered.

**Project Description and Definitions**

The vertical shaft at Taum Sauk is a 137 m (450 ft) deep, 8 m (26 ft 2 inch) diameter shaft, lined with concrete in the top 40 m (130 ft). The top of the vertical shaft is located in the southwestern portion of the upper reservoir in a localized area that is 6.1 m (20 ft) lower than the rest of the reservoir floor to suppress vortex development. The vertical shaft transitions to a 1453 m (4,765 ft) long, 7.6 m (25 ft) diameter horseshoe-shaped unlined tunnel that slopes at 5.7 percent. A 26.5 m (87 ft) long concrete-lined transition section connects the unlined tunnel to the 551 m (1807 ft) long, 5.6 m (18 ft 6 inch) diameter steel-lined section of the outlet works. The steel-lined section of the outlet works has two sections. The steel-lined tunnel is the 195 m (640 ft) long section of the outlet works where the steel liner is designed to share the internal pressure load with the surrounding rock. The 355.8 m (1167 ft) long penstock has a steel liner that is designed to take full static and dynamic head without any resistance from the surrounding rock.

The entire outlet works is underground, with the exception of a small section of the penstock near the downstream end that is exposed. A short section of the penstock near the powerhouse bifurcates to the pump-generating plant. Two 9-foot-diameter spherical valves in the powerhouse control flow through the outlet works. For the purposes of this Paper, “upstream” is in the direction of the upper reservoir, while “downstream” is in the direction of the powerhouse. There are two 4.6 m (15 ft) wide by 6.1 m (20 ft) deep rock traps in the outlet works; one is located immediately downstream of the vertical shaft and the other is immediately downstream of the unlined tunnel.

**OUTLET WORKS INSPECTION PROGRAM**

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The majority of the inspection work was performed October through December of 2006, prior to the start of the rebuild of the upper reservoir. The upper reservoir was out of service at the time so the upper reservoir, vertical shaft, unlined tunnel, steel-lined tunnel, and penstock were dewatered during the inspections.

**Inspection Description and Results**

The overall objective of the outlet works inspection was to obtain all the data required to determine the “fitness-for-service” of the system. Specific objectives included:

- Develop a photographic condition record of the interior of the outlet works;
- Determine the integrity of the outlet works, especially the unlined portions of the vertical shaft and unlined tunnel;
- Obtain radar scans of the vertical shaft to determine integrity of the shotcrete and underlying rock;
- Observe the vertical shaft during pressurization of two borings near the vertical shaft to investigate connection between the vertical shaft and the reservoir floor;
- Investigate conditions and dimensions at the transition from the vertical shaft to the unlined tunnel, at the turns in the unlined tunnel, and at the transition from the unlined tunnel to the steel-lined tunnel for future accessibility;
- Identify and report on previous inspection areas of concern, specifically the buckled and cracked section of the steel-lined tunnel;
- Obtain data on steel liner alignment and out-of-roundness; and
- Obtain a representative number of thickness readings of the steel liner.

**Vertical Shaft Inspection.** Two separate inspections of the vertical shaft were conducted; an unmanned inspection using ground-penetrating radar (GPR) and a camera, and a manned inspection using a crane and an inspection basket. The unmanned inspection consisted of lowering a cart equipped with a camera and two frequencies of GPR into the shaft as shown in Figure 2. The cart was lowered at eight points around the vertical shaft to allow the GPR and camera to scan a representative area of the shotcrete and rock. During the manned inspection, a basket was lowered into the vertical shaft. Soundings of the shotcrete liner were performed with a hammer where possible and a visual inspection was conducted. To investigate the permeability of rock and the shotcrete liner, two borings near the vertical shaft were pressurized and the lined section of the vertical shaft was observed for water leakage. Results of packer...
testing and pressure testing during the shaft inspection indicated a connection between the top 6.1 m (20 ft) of the vertical shaft, the surrounding rock, and the floor of the reservoir. Inspection of the unlined section of the vertical shaft was difficult due to water flowing into the top of the shaft during the inspection.

FIGURE 2: CAMERA AND GPR INSPECTION OF VERTICAL SHAFT

The rock walls of the unlined section of the vertical shaft were generally in good condition. No erosion was observed, and although the walls of the tunnel were rough, no large pieces of rock were observed to be missing. During the unmanned inspection of the vertical shaft, one area was discovered where the shotcrete had deteriorated through to the surrounding rock, exposing the original reinforcing mesh as shown in Figure 3. Video footage taken during the unmanned inspection was confirmed by the manned visual inspection.

FIGURE 3: HOLE IDENTIFIED IN SHOTCRETE LINING IN VERTICAL SHAFT
Unlined Tunnel Inspection. A typical wall of the unlined tunnel, constructed in the early 1960’s by drill-and-blast methods, is shown in Figure 4. As part of the outlet works inspection program, a visual inspection of the unlined tunnel was performed and geologic mapping was done by a geologist. The unlined tunnel was in good condition overall. The rock exposed in the unlined tunnel was classified as granite and is generally slightly weathered to fresh, with localized areas that are intensely weathered. Rocks of varying size were found on the floor of the unlined tunnel, some of which were up to approximately 1.5 m (5 ft) in diameter and 1.2 m (4 ft) thick. No large holes or missing pieces of rock were observed in the walls or ceiling near the large pieces of rock found on the floor of the tunnel. There were areas on the walls and roof of the unlined tunnel that had been patched with rock anchors and/or shotcrete were observed during the inspection, these were likely to prevent erosion of less competent rock because rock anchors and shotcrete were not called for on the original design drawings.

A fracture zone crossing the unlined tunnel was mapped approximately 300 m (1000 ft) downstream from the vertical shaft. Granite along the fracture had been eroded from the roof and walls of the unlined tunnel, creating a trench into the roof and walls along the fracture. This trench varied in depth from 0.3 m to 1.5 m (1 to 5 ft) and was from 75mm to 150mm (3 to 6 inches) wide. Rock anchors were installed along the fracture
during original construction, but much of the granite had fallen away from the anchors or had been eroded.

At the time of inspection, the rock trap near the vertical shaft was approximately one-half full, and the rock trap near the lined tunnel was approximately two-thirds full. Large boulders could be seen in each rock trap, with some of the boulders measuring up to 1.5 m (5 ft) across.

FIGURE 4: TYPICAL WALL OF UNLINED TUNNEL

Steel-Lined Tunnel and Penstock Inspection. The steel lined tunnel and penstock were constructed of 3.3 m (10 ft 8 inch) long “cans”. The thickness of the liner varies from 16mm (5/8 inch) to 47.6mm (1 7/8 inch). Each can has a circumferential weld at its upstream and downstream ends and two welds along the axis. Inspections for the steel-lined tunnel and penstock included a visual inspection, a survey, and ultrasonic testing. The internal drains, buckling, and cracking in the steel-lined tunnel were also observed and measured.

An alignment survey of the steel-lined tunnel and penstock was performed to check vertical alignment, verify dimensional accuracy of existing drawings, and check sectional roundness. A bottom (invert) elevation survey was performed for the entire
length of the steel-lined tunnel and penstock. The penstock and steel-lined tunnel were also checked for out-of-roundness (ovality) at 52 sections.

Ultrasonic testing was performed to check the thickness of the steel liner in the steel-lined tunnel and penstock and verify design drawings. Readings were taken at ten sections in the penstock and at twelve sections in the steel-lined tunnel. The thickness of the liner in the penstock and steel-lined tunnel varies, so at least one set of readings was taken for each liner thickness. A total of 88 readings were obtained. Approximately 70% of the UT readings indicated a thickness greater than or equal to the design thickness for the liner. A statistical analysis was also performed on the UT data to determine if any significant corrosion had occurred. This analysis showed significant corrosion had not occurred and corrosion of the existing liner was not a problem.

The penstock and the downstream portion of the steel-lined tunnel were in good condition. No bulging, discontinuities, or cracks were observed during the inspection. Soundings were performed in several locations with a hammer, but no voids were found.

The upstream portion of the steel-lined tunnel showed evidence of prior buckling, and a 6.7 m (22 ft) long crack near the invert of the steel liner was observed near Sta. 15+00 at the time of inspection, as shown in Figure 5. This area had cracked and buckled on several previous occasions, and had been weld repaired and patched several times. Soundings and visual observations near the crack indicated that there were significant voids between the liner and the surrounding concrete. Four sets of internal drain pipes, each of which was 76.2 mm (3 inches) in diameter, were previously installed to run parallel with the steel-lined tunnel at the cracked section, apparently to provide additional drainage in this area or because the original external drainage system was not functioning as intended.

**FIGURE 5: CRACK IN INVERT OF STEEL LINED TUNNEL**
REHABILITATION DESIGN AND OPTIONS ANALYSIS

Based on the results of the inspection of the outlet works, an assessment of the rehabilitation required to restore the long-term functionality and reliability of the outlet works was performed and used to develop a rehabilitation program. A summary of the assessment, options analysis, and design for each section of the outlet works is presented below.

**Vertical Shaft.** Because the vertical shaft was generally in good condition, the repairs designed were minimal. The GPR scans indicated voids between the shotcrete and the surrounding rock in some locations, so grout rings at 3 m (10 ft) vertical spacing were designed in the lined section of the vertical shaft. The maximum grout pressure in these rings was limited to prevent damage to the existing shotcrete liner. Additionally, a fix for the hole in the shotcrete that was identified was designed that included dowels, reinforcing mesh, and shotcrete.

**Unlined Tunnel.** The only area requiring remediation in the unlined tunnel was the fracture zone at approximately Sta. 51+00. To stabilize this area and prevent future rockfalls that could damage the turbines, a fix for the fracture zone was designed that
included rock bolts, reinforcing mesh, and shotcrete. The remediation was designed to restore the original shape of the unlined tunnel at this location.

**Steel Lined Tunnel and Penstock.** The investigation and analysis of the upstream portion of the Steel Lined Tunnel where the steel liner is 16 mm (5/8 inch) thick indicated that the liner buckled several times over the history of the project as a result of external pressure during dewatering of the outlet works. The buckling was due mainly to a blocked external drain system. The cracking and buckling in this distressed section had been repaired previously on several occasions by welding but the repairs did not survive.

An engineering evaluation concluded that the rock surrounding the cracked section of the steel-lined tunnel was competent and that "blow-out" of this section was not a concern. However, repair of the cracked and previously-buckled section by relining was recommended. The initial recommendation was to reline the tunnel with new 5.2 m (17 ft) diameter cans. These cans would be installed inside the existing steel liner, and thus would have a smaller internal diameter than the as-designed water conduit. After a reevaluation and estimate of the cost, it was decided that patch plates would be welded along the invert of the existing liner in the cracked section only to reduce costs and eliminate hydraulic losses associated with the smaller internal diameter of the new cans.

The design for the rehabilitation of the steel-lined tunnel also included the installation of a grout ring at the upstream end where it transitions from the unlined tunnel to reduce flow along the outside of the tunnel and consolidation grouting at a location where high water inflows were present during original construction of the outlet works. Embedment grouting was also performed to ensure there was contact between the existing liner and the surrounding concrete and grout.

New drains were included in the design in a portion of the steel lined tunnel as part of the rehabilitation. The existing drains in this section were located on the inside of the liner and were likely not functional. The new internal drains were connected to the existing external drains at approximately Sta. 14+00. Access ports were cut in the existing liner at Sta. 6+00 and Sta. 12+00 to clean the existing drain system, and the access ports were fitted with a removable cover for future cleaning if necessary.

**CONSTRUCTION**

Construction began during January 2009 and continued through December 2009. The majority of work was performed during a day shift; a second shift was added during November 2009 to complete work.

The major components of the work were:
• Installation of 33.5 m (110 ft) of patch plates along the invert of the existing steel-lined tunnel in 11 sections from Sta. 14+20 to 15+30 and grouting between the existing liner and patch plates;
• Contact grouting of the existing liner;
• Consolidation grouting of the rock surrounding the tunnel at Sta. 15+05;
• New internal drain system from Sta. 14+20 to 18+01, cleaning of the external drain system, and installation of access portals for the existing external drain system at Sta. 6+00 and 12+00;
• Installation of rock anchors, mesh, and shotcrete at Sta. 51+00 of the Unlined Tunnel;
• Grouting between the shotcrete lining and the surrounding rock in the Vertical Shaft;
• Repair of a hole in the shotcrete in the Vertical Shaft; and
• Cleaning of the rock traps.

Photos of various components of the work are provided in Figures 6 to 10 below.

FIGURE 6: INSTALLATION OF PATCH PLATES ALONG INVERT

FIGURE 7: CONTACT GROUTING OF STEEL LINED TUNNEL
FIGURE 8: ACCESS PORTAL FOR DRAIN CLEANING
FIGURE 9: COMPLETED REPAIR IN UNLINED TUNNEL AT STA 51+00

FIGURE 10: REINFORCING MESH FOR REPAIR OF VERTICAL SHAFT
Environmental Measures During Construction

A temporary dam was constructed within the penstock to control runoff during construction. Water collected behind this dam was monitored for traces of oil. Clean water collected by the dam was pumped to tanks and emptied at an on-site location. Contaminated water was collected separately and disposed of.

Safety and Access

The outlet works was accessed two ways during construction. The majority of the time access was through a man door in the powerhouse or through a small access portal into the downstream end of the penstock. The general contractor had an employee at each entrance portal to sign workers in and out, and a sign in/out sheet was posted to track the number of employees in the outlet works.

Because the entrances at the downstream end of the penstock were small, construction materials and large equipment for work in the unlined tunnel and penstock were lowered into the outlet works using a crane from the top of the vertical shaft. To perform the repair and grouting work in the vertical shaft, a platform was lowered from the top of the shaft. This platform could be raised and lowered as required. Each person riding the platform was equipped with a harness which was attached to the platform and a life line anchored at the top of the shaft.

Ameren held a training program for every person that was required to work in the outlet works. The program discussed emergency procedures, sign in and sign out procedures, whom to notify when going into the penstock or vertical shaft, and air monitoring.
devices. Because the entire outlet works is a confined space, each group of personnel was required to have an air monitoring device. Prior to the start of work a system was developed to retrieve a person if they became incapacitated. The system consisted of a gurney that would be lowered into the penstock to retrieve the individual. In addition, Ameren had at a minimum 1 registered nurse on duty at the site at all times during work.

**Construction Challenges**

In early July 2009, cracks were identified in the welding performed at some of the drain cleanout access locations at the welds. Ultrasonic and magnetic particle testing were performed to determine the extent of cracking. The cracking was due to incompatibility of the welding rods used with the existing penstock steel. Repair of the identified cracks was performed during August 2009 with certified weld supervision. A new welding procedure was utilized for the welding of the remaining drain cleanout locations. Welding continued through December 2009 with additional testing showing satisfactory results.

In August 2009 during consolidation grouting at Sta. 15+05, a bulge occurred near the invert of the existing liner. The bulged area was approximately 6.7 m (22 ft) in length by 1.2 m (4 ft) in width and up to 250 mm (10 inches) in depth. A procedure was developed for repair and a revised grouting procedure was developed. The grouting procedure was changed to limit the amount of grout permitted in a hole and to have pressure gauges placed and monitored at the point of grouting and at the grout mixer. The gauges were also outfitted with a needle that indicated the maximum pressure achieved when grouting. Repair of the bulge began during October 2009 and continued through early November 2009. Repair consisted of heating the steel and jacking the bulge back into place as much as possible, which was generally between one and two inches. The bulge area was then grouted at a maximum pressure of 35 kPa (5 psi). 208 liters (55 gallons) of grout were pumped into the bulge area.

**FIGURE 11: JACKING TO REPAIR BULGED SECTION**
FIGURE 12: REPAIRED BULGED SECTION
A blockage was encountered in the external drains at approximately Sta. 2+75 in both upper drains. The drains could not be unplugged, so two crossover pipes were designed to connect the upper drain headers to the lower drain headers at approximately Sta. 14+22.

**SUMMARY**

The Taum Sauk Pumped Storage Plant, which originally began operation in 1963, had a catastrophic failure of the upper reservoir in 2005. During the construction of the new upper reservoir dam, the entire outlet works consisting of a 137 meter (m) (450-foot (ft)) deep shaft and over 1830 m (6,000 ft) of lined and unlined tunnels, were inspected and rehabilitated. Overall, the shaft and unlined portion of the tunnel were in good condition and required only minimal repairs. Patch plates were installed in areas of the steel-lined tunnel where cracking was found, and an improved drainage system was installed. Consideration for environmental issues and the safety of personnel performing the work was provided throughout. The Upper Reservoir, including the Outlet Works, was put back into service in April 2010.