

Raw Water Tunnel Condition Assessment

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ABSTRACT: As part of its risk management plan, the South Central Connecticut Regional Water Authority (RWA) is assessing the condition of its system of raw water conveyance tunnels and connecting pipelines. In 2006, the RWA inspected one of the system's main tunnels, a 4-mi, 1950s-era tunnel that had not been inspected since its construction. The inspection team prepared extensively for the unknown conditions in the tunnel, and the inspection was completed safely and successfully. This paper describes the team's pre-entry preparations, dewatering and ventilation efforts, surface-to-tunnel communication, access, physical inspection of the tunnel, and the lessons learned throughout the process. Additionally, this paper will preview planning for the subsequent inspections.

THE HISTORY OF THE RWA SYSTEM

The South Central Connecticut Regional Water Authority (RWA) owns and operates an extensive water supply and distribution system which serves 410,000 customers in 15 municipalities in the south central region of Connecticut, making it the largest water utility in the state, in terms of population served. The RWA service area is shown in Figure 1.

The RWA currently operates four surface water treatment facilities and five groundwater treatment facilities, providing approximately 55 million gallons of water-per-day to its customers. The RWA also operates and maintains approximately 1,700 miles of distribution piping, 37 water storage tanks, and 37 pumping stations, and owns and protects watershed land in the region. Connecticut is the only state in the U.S. that only allows Class 'A' water (water that does not contain any wastewater effluent) to be used for potable water sources. Thus, it is vital that the RWA preserve watershed land. Since its creation, the Authority has been able to protect over 26,000 acres of watershed land.

Several of the RWA's surface water reservoirs are not located near a water treatment facility, necessitating the use of underground aqueducts, both conduits and tunnels, to move water into treated reservoirs. The RWA considers all buried pipelines to be conduits, and any bored, blasted, or otherwise mined aqueduct is considered a tunnel. In all, the

RWA owns 15 conduits and tunnels, ranging in size from 3.5 ft in diameter with an approximate capacity of 20 million gallons per day (MGD), to 6 ft, 8 in in diameter with an approximate capacity of 160 MGD. The oldest conduit in the RWA's system was constructed in 1864. While this particular supply line is not currently in use, most of the other 14 lines are. The most recently constructed tunnel, completed in 1956, is the main tunnel in this portion of the RWA system.

CATALYST FOR INSPECTIONS: THE RWA'S RISK MANAGEMENT PLAN

The RWA's operations are critical to the health and well-being of over 400,000 people and businesses in south central Connecticut. It is imperative that the RWA maintain a reliable, high-quality water distribution network and treatment system to provide potable water for residential, commercial, industrial, and public authority uses. Continued service reliability is only possible through the RWA's comprehensive and well managed asset-based risk management program. In 2006, the RWA initiated a risk management plan that involved an initiative to inspect all of its above-ground and buried assets. The RWA plans to inspect all tunnels and conduits to determine their baseline conditions, then plan repair work based on the urgency of the necessary repairs.

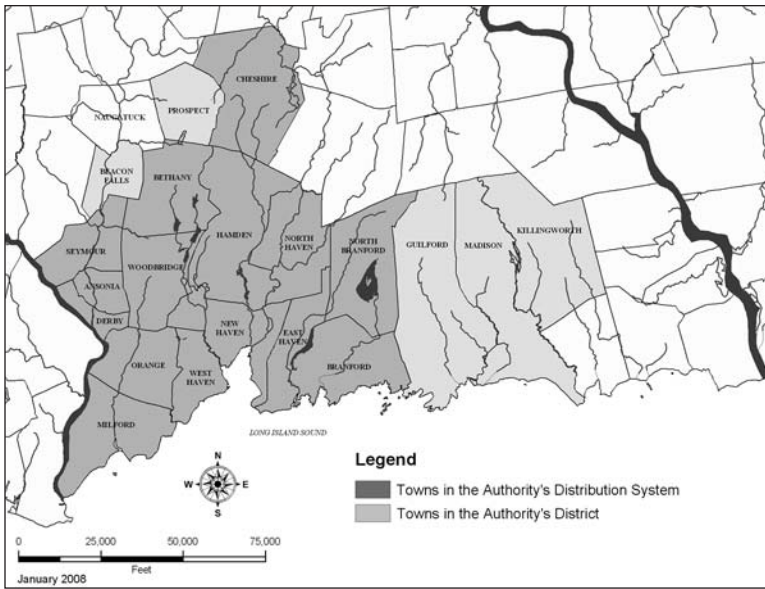


Figure 1. Limits of the Regional Water Authority District

Although this plan requires that tunnels be removed from service and dewatered multiple times, the RWA decided that its own lack of experience in this type of work required a more cautious approach that justified the associated additional costs.

In planning the inspections of its system, the RWA prioritized inspection of a series of tunnels and conduits that bring water to the Authority's largest water treatment plant. This portion of the system includes approximately 43,000 lf (8.1 mi) of tunnels and conduits. The first of these facilities to be inspected was Tunnel 1, completed in 1957. Tunnel 1 is one of the more remote tunnels in the RWA system, and has not been inspected since it was constructed. To assist with the inspections, RWA retained Jacobs Associates (a tunnel engineering firm) and a group of confined-space entry and rescue professionals. RWA employees directly involved in the operation and maintenance of the tunnels and conduits also participated in the physical inspections.

CONDITION ASSESSMENT OF TUNNEL NO. 1

Background

Tunnel 1 was taken out of service and inspected in December 2006. The tunnel was built between 1955 and 1957 to transfer untreated water from an upstream reservoir/watershed to reservoirs at lower elevations closer to the water treatment plant. It is used on a yearly basis, typically in the spring and

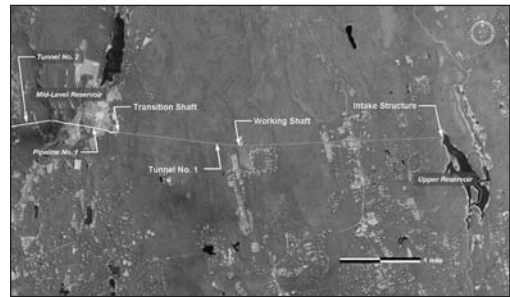


Figure 2. Alignment of Tunnel No. 1

fall, to transfer collected water from the upper watershed. The RWA engaged Jacobs Associates to conduct a physical inspection, including preparation and support service administration.

There are three major points of access to the tunnel: the Intake Structure, located at the upstream end of the tunnel at the upper reservoir (Sta. 215+16); the Working Shaft, which was the original construction shaft and is located near the mid-point of the tunnel (Sta. 80+35) and is also the deepest part of the tunnel; and the Transition Shaft, which provides a transition to a near-surface pipeline at the downstream end of the tunnel (Sta. 0+00). Figure 2 shows the general arrangement of the tunnel and the three access points.

The tunnel was constructed through the Ordovician-age Middletown Formation and the

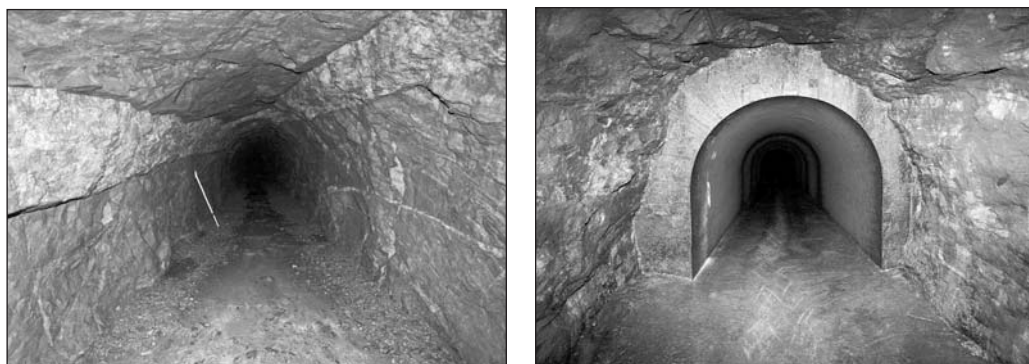


Figure 3. Typical photographs of the unlined and lined sections of Tunnel No. 1. Note the prominent pegmatite dike cutting the gneiss foliation.

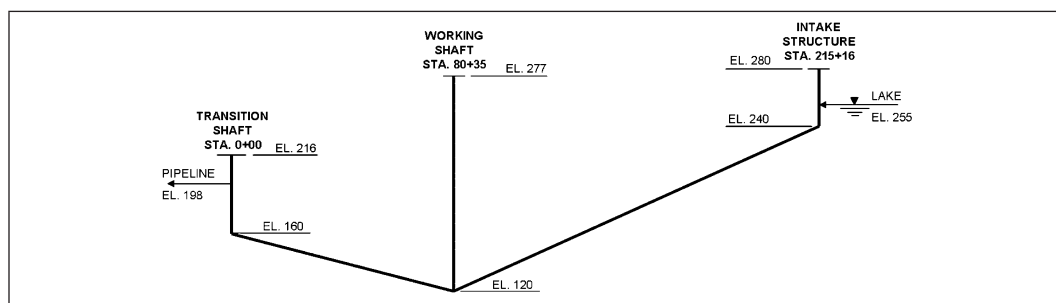


Figure 4. General arrangement of Tunnel No. 1

Monson Gneiss. Both units consist predominantly of quartz biotite gneiss and amphibolite. The tunnel was constructed by drill-and-blast methodology. The as-built construction records of the tunnel, which were confirmed by the inspection, indicate that the tunnel is 41% unlined and 59% lined with cast-in-place concrete. The lining was placed in areas of adverse rock conditions where long-term stability of the tunnel opening was considered uncertain or where groundwater inflows were excessive. Photographs of the unlined and lined tunnel are provided in Figure 3.

The tunnel is horseshoe-shaped and is 21,516 ft long. It varies in size from 6'-8" by 6'-8" in the lined portion to 9'-2" by 9'-2" in the unlined portion. The tunnel operates as an inverted siphon between the upper reservoir and the near-surface pipeline, see Figure 4. During operation of the tunnel, the gates at the Intake Structure are open, allowing water to flow by gravity through the tunnel from the reservoir to the pipeline. The pipeline connects to the Transition Shaft at El. +198 and, depending on the lake level, a 57-ft or higher driving water head is provided to the gravity-fed pipeline downstream. The tunnel invert

elevation at the Intake Structure is El. +240 and the invert elevation at the Transition Shaft is El. +160. With closure of the Intake Structure gates, water drains into the downstream pipeline until it reaches equilibrium at the invert of the pipeline exiting the Transition Shaft, El. 198. At equilibrium an estimated 12 million gallons of water remained in the tunnel; this water had to be mechanically removed for the inspection. Dewatering required the use of submersible pumps at the lowest point in the tunnel (the Working Shaft, which is at El. +120).

Pre-Entry Planning

Safety must be a high priority for any tunnel inspection. Initial planning sought to identify potential hazards the inspection team would face and develop mitigation measures. Since the tunnel is an inverted siphon, provisions to dewater the tunnel were required. Then, once the tunnel was dewatered, the hazards would include tunnel instability, atmospheric hazards, and operational hazards. To mitigate those hazards, an extensive entry plan was developed to address personnel accountability and access, ventilation, deep penetration confined space

entry, communications, personal protective equipment (PPE), first aid and stand-by rescue services.

Tunnel Instability Hazard Mitigation

The tunnel had not been completely dewatered in nearly 50 years and the condition of the concrete lining was uncertain. The pumps withdrew the water at approximately 2,000 gpm which reduced the vertical head in the tunnel (and from behind the linings) at a slow rate. This allowed time for the stresses in the tunnel to equalize after dewatering. The inspectors were prepared to look for and scale any loose rock in the crown. We also made plans for encountering zones where the tunnel might have partially collapsed, forcing us to turn around and exit at the original entry point.

Atmospheric Hazard Mitigation

We considered that the seasonal operation of the tunnel could allow organic material to be deposited on the tunnel surfaces (organic material was in fact found to completely cover unsubmerged areas of the floor). Unsafe oxygen and hydrogen sulfide (H₂S) levels were a possibility due to the aerobic decomposition of this organic material. In stagnant water with low oxygen content, H₂S is often produced when bacteria break down plant and animal materials. To guard against an unsafe atmosphere, we monitored the air quality for unsafe levels of oxygen and H₂S. The inspection team carried three such monitors, two for use and one as a back-up. The team could not count on natural air flow despite the difference in elevation between the various access points, so provisions were made for mechanical ventilation by adding a fan at the Transition Shaft to pull air through the tunnel. Organic material including black and brown mosses are typically encountered in raw water supply tunnels, which can make surfaces slippery, increasing the potential for falls and related injuries. Inspectors carried walking sticks for stability and walked downstream when possible.

Operational Hazard Mitigation

The most significant operational hazard on the inspection was the potential for flooding. Flooding was prevented through a lock-out-tag-out (LOTO) protocol that isolated the tunnel from the rest of the RWA system. Two forms of LOTO exist in most municipalities: physical and administrative LOTO. Administrative LOTO places a clearance tag or man-on-line tag (typically paper) on equipment control surfaces. Operators are trained not to place equipment in service if a tag is present. Physical LOTO requires that equipment be temporarily disabled or prevented from operating. For this inspection, fuel supply to the generator that is used to automatically operate the intake structure sluice gates was closed and tagged. In addition, the individual valve operators at the intake structure were locked to prohibit

inadvertent operation. Diversions and inlets from local streams were physically secured. Blow-off valves downstream of the tunnel were opened to drain. What the inspection team did not know prior to the inspection was how much infiltration and seepage was occurring into the tunnel through the ground. Since submersible pumps were needed initially to dewater the tunnel, they were left in place during the inspection to pump out any infiltration. Dewatering operations are covered later in this paper.

Access to this tunnel is difficult. The depth from the surface to the tunnel invert varied from 40 feet at the Intake Structure to 157 feet at the Working Shaft. As-built drawings of the Intake Structure showed ladders mounted on the walls for access, but we did not know the condition of these ladders. To safely access the tunnel at the Intake Structure, a combination of fall protection and extension ladders were used in lieu of the existing ladder system. Once the inspection team began working in the tunnel, a portion of one of these existing ladders was found to have been washed into the tunnel itself. The remaining ladder sections in the Intake Structure were found to be weakened by the repeated push of water from the reservoir and were not suitable for use in accessing the bottom of the structure. We made provisions for a personnel rated crane and cage/basket to lower the inspectors into and haul them out of the tunnel at the Working Shaft, as there were no existing means to descend to the tunnel invert at this point. Tripods, with fall prevention, were used to enter and exit the tunnel at the Intake Structure and Transition Shaft locations. Inspectors wore safety harnesses at all times during the inspection.

Communication between surface support teams and tunnel entrants is typically problematic in in-service water tunnel inspections. Jacobs Associates has explored many communication methods in the past, but no one method is completely effective. The inspection teams carried radios for voice communication but found that effective communication was limited to about 2,000 ft and only if a line of sight was maintained. On the surface, a safety officer maintained radio contact with surface personnel stationed at the other two points of access. Radio contact between the surface and the tunnel was lost when the line of sight was interrupted. Attendants were positioned at the bottoms of the Working Shaft and Intake Structure to relay between surface personnel and the tunnel entrants. Generally, radio communication was effective at distances up to about 2,000 ft by line of sight between the inspection team and the attendants positioned at the bottom of the shafts. The teams also carried air horns, which could be used for signaling. Unfortunately this technique was only effective to about 1,000 ft.

To safeguard the inspection team in the event that communication was lost during an underground emergency, the inspection party included two emergency medical technicians trained in tunnel rescue. The inspection party was also large enough that two entrants could be sent for help while the remainder of the entrants attended to the injured.

Personal protective equipment for the tunnel entrants was selected to protect against the identified hazards. The required personal protective equipment included:

- Hard hats
- Helmet mounted lights
- Flashlights, back light, and spare batteries
- Safety glasses
- Dust masks
- Atmospheric monitoring meters
- Gloves
- Thermal shirt
- Water repellant jackets
- Walking sticks
- Waders with sturdy boots
- Emergency whistles, air horns, and radio
- First aid kits
- Hand cleaner/sanitizer
- Water and snacks

Prior to the inspection, the tunnel entrants and support team participated in a full-day safety training. The training included:

- Overview: Purpose of inspection, access, anticipated conditions, safety procedures, and emergency procedures
- Safety instruction: Recognition and avoidance of hazards, air monitoring, ventilation, illumination, communications, potential for flooding, LOTO, use of personal protective equipment (including breathing apparatus), fire prevention and control, emergency procedures such as evacuation, and personal accountability requirements
- Requirements for completing the Permit Required Confined Space/Tunnel Entry Permit: Specific actions required to be completed prior to entering the tunnel

Prior to entry, the entry permit was updated with the hazards assessment, incident action plan, communication plan, LOTO, personnel accountability plan, personal protective equipment, and atmospheric monitoring equipment. After satisfying themselves that the permit requirements had been met, the inspection supervisor, the safety officer, and the RWA's work supervisor reviewed and signed the permit.

Support Services Contract

The RWA recognized that its personnel did not have the specialized equipment and skills to support certain aspects of the tunnel inspection. A Support Services Contract was developed for the RWA to procure services to dewater the tunnel, install a ventilation system, and hoist personnel from the Working Shaft. The RWA received several bids for the work and awarded a contract to Xenelis Construction Company, of Middlefield, CT. The efforts by Xenelis to dewater and ventilate the tunnel are described below.

Dewatering Support Services

The tunnel was taken out of service by closing the gates at the Intake Structure and valves at several stream diversions. Once the tunnel was taken out of service, approximately 12 million gallons remained in the tunnel, leaving 70% percent of the tunnel entirely or substantially underwater. This water had to be removed before the inspection, and groundwater inflows had to be removed during the inspection. The Support Services Contract included performance specifications for completing the initial dewatering effort and dewatering required during the inspection. The contract required Xenelis to develop and implement a dewatering plan and included the following criteria for planning the work:

- Remove the stored water (12 million gallons) from the tunnel at the Working Shaft.
- Pump at a maximum discharge rate of 2,000 gpm (limitation included in the RWA's discharge permit from the Connecticut Department of Environmental Protection) until the tunnel is empty.
- Perform maintenance pumping during the five-day inspection to handle groundwater inflow of up to 750 gpm.
- Provide in-place back-up pumping capacity while the inspection team is in the tunnel.
- Install the pumps from the surface (no contractor personnel are allowed entry into the tunnel).

To accomplish the dewatering, Xenelis installed two Godwin SubPrime GSP900 electric driven submersible pumps at the base of the tunnel at the Working Shaft. These pumps were capable of pumping 5,000 gpm at 360 ft head, more than enough for the project. The surface and tunnel invert elevations at the Working Shaft are El. +276.5 and El. +120 feet, respectively. Prior to dewatering, the water level in the shaft had reached equilibrium at El. +198, or 78 feet from the base of the shaft. While the pumps were easily capable of pumping the total head from the invert of the tunnel to the ground surface, the pump motor electrical seals were rated for only



Figure 5. Dewatering pumps at the base of the working shaft

60 feet of submergence. The dewatering plan included a two-stage dewatering operation for pumping out the stored water. The pumps were first lowered to El. +160, the initial dewatering elevation. Once dewatering at this elevation was accomplished, the pumps were lowered to the invert of the tunnel without concern for breaching the electrical seals. The pumping system worked well to dewater the tunnel and maintain the low water level required throughout the inspection. During the inspection, the pumps were run for 10 minutes every hour to maintain a low water level at the Working Shaft. Figure 5 shows the pumps at the base of the Working Shaft between active pump-out cycles.

Ventilation Support Services

The Support Services Contract required the contractor to install and operate a fan to provide a minimum air flow of 200 CFM per entrant. The criteria for air flow during the inspection were set by the RWA and intended to exceed the Connecticut Occupational Safety and Health Administration (OSHA) and FedOSHA requirements for ventilation. The general industry safety orders are applicable to this inspection since the tunnel is in-service and not in construction or a mine. The contractor satisfied this flow rate requirement by installing a ventilation fan at the Transition Shaft end of the tunnel. The fan selected by the contractor was a 24-inch Dayton Fan which was capable of 3,400 cubic feet per minute (CFM) at a static head of 1/2 in-wg. The fan was capable of reversing the direction of air, and was operated in suction mode during the inspection. Fresh air would enter the tunnel at both the Intake Structure and the Working Shaft. When the tunnel between the Working Shaft and Intake Structure was inspected, a bulkhead was installed at the Working Shaft to prevent

ventilation short-circuiting. The ventilation system worked well. The tunnel air flow was routinely measured throughout the inspection. While the air flow was consistent, the air speed varied inversely with the changing tunnel cross section.

Inspection Methodology

The objective of the inspection was to visually inspect and evaluate the current condition of the tunnel. The inspection party worked in two functional groups. The lead party performed the tunnel integrity check, scaled hazard rocks as necessary, measured for and installed survey markers, and marked the stationing of the concrete lining starts and stops. The second party performed the condition assessment, including geologic interpretation of the tunnel condition, identification and recording of anomalies (voids, seeps, features, and debris), measurement of cross sectional dimensions, measurement and recording of seeps and water inflow, and photographing of tunnel conditions.

Inspection Results

The tunnel and associated shafts were found to be in excellent condition, overall. Groundwater inflow into the tunnel was approximately 100 gpm, based on the dewatering pump-out rate. Fifty-six gpm were measured from visual seeps into the tunnel. The presence of drill holes used for blasting during excavation indicates that the tunnel is competent and has withstood weathering and erosion effects since it went into operation. In all the unlined sections, the tunnel is bald headed with no support. In addition, there were not a significant number of fractured rock/wedges found in the invert that would indicate instability. The inspectors found the typical mud/sand/fines that would be expected due to normal weathering and erosion.

The lined sections of the tunnel are in excellent condition, with few or no voids. Most of the concrete surfaces were smooth and moss-free. The welding beads for the steel forms used in the original construction were still visible on the concrete surface. Calcite deposits were present along some of the lined sections where the tunnel is above the free-draining water level.

It appears that the sluice gates at the Intake Structure were opened quickly over the years. The fast in-rush of water that this created has, over time, eroded the invert of the upstream unlined section of tunnel. The sand and gravel fill normally found in the tunnel invert has been transported downstream to around Sta. 178+00, which is just upstream of where the tunnel remains filled with water.



Figure 6. The portion of the tunnel above the “stored” water level lined with mud in the invert, which made walking difficult

Lessons Learned

Following the inspection, the participants developed a list of lessons learned throughout the course of the project:

- Walking down grade (in the direction of flowing water) is generally easier for an inspection team. However, in this tunnel the inspection team found it was easier to walk up grade, due to the excessively slippery floor surface caused by the organic growth. In addition, there were no significant groundwater inflows that could make walking up grade and against flowing water more difficult. The upper portion of the tunnel invert near the Intake Structure was covered with a thin layer of mud (see Figure 6). Walking down grade with the mud on the first day was more difficult than walking up grade on the second day. The difference was most noticeable in the upstream unlined sections near the Intake Structure, where the invert was uneven and coated in mud (see Figure 7).
- Due to the mud in the invert, inspectors were uncertain of their footing and often slipped. Although everyone slipped, no one sustained any related injuries. Inspectors used different methods to improve boot traction, including ice grippers, felt soles, Vibram soles, and walking sticks. Inspectors who wore ice grippers walked right out of them and ended up taking them off. Using walking sticks and walking up grade provided the best traction.
- While communication between the separate crews in the tunnel was adequate, surface-to-tunnel communication could have been better. Working underground can be very dangerous, and a reliable communication method should



Figure 7. The first unlined tunnel also showed residual mud in the invert, which made walking difficult. Note the remnants of the one of the ladders from the intake structure.

be further explored. The team discussed using lighting signals, colored lights, and a hard-wired tunnel-to-surface phone. For the future inspections, we are planning to use a “leaky” cable system to improve surface-to-tunnel communications.

FUTURE INSPECTIONS PLANNED

With the success of its first inspection, the RWA plans to continue condition assessments of its other underground assets. The RWA Risk Management Plan schedule calls for inspection of one segment of tunnel or pipeline per year. Based on the configuration of its system, the RWA has determined that it will be cost-effective to include two segments in its next inspection. Currently, the RWA is preparing to inspect two segments downstream of Tunnel 1. They include 3,635 ft of 54-in-diameter pre-stressed concrete cylinder pipe and 14,650 ft of lined horseshoe-shaped tunnel.

Pipeline Inspection—Pipeline No. 1

Pipeline No. 1 consists of a 54-in-inside-diameter prestressed concrete cylinder pipe (PCCP) and is 3,635 feet long. It conveys water from the downstream end of Tunnel No. 1 to just upstream of the mid level reservoir connecting with Tunnel No. 2.

The pipeline’s vertical alignment generally follows the surface topography with a minimum of three feet of soil cover over the top of the pipe. While a majority of the alignment has grades of less than 12 percent, several short lengths of alignment, totaling 200 feet, contain relatively steep grades of between 22 and 35 percent.

There are several structures connected to the pipeline. These structures serve several purposes during the operation of the pipeline and will be utilized for specific purposes during the inspection. These structures include:

- Transition Shaft at Sta. 37+63 for personnel access and fresh air intake
- Blow off structure at Sta. 21+13 for dewatering
- Air valve with manhole at Sta. 16+95 for personnel access
- Pump Out at Sta. 14+60 for dewatering
- Air valve with manhole at Sta. 13+55 for personnel access
- Blow off structure at Sta. 8+40 for dewatering
- Venturi meter at Sta. 1+20 for personnel access

The pipeline inspection will present more difficult conditions given its size. It is noted that an inspection of this pipeline had been completed previously, in 1991. The 1991 inspection report describes very difficult mobility due to slime build up on the walls of the pipe and no success in moving through the steeper grades noted above. Several changes to the inspection plan and scope of work used for Tunnels No. 1 and No. 2 are planned for the pipeline inspection. These include:

- Inspection crew of three entrants rather than nine
- Rope assists will be required to “climb” the steeper slopes
- Permanent stationing will not be installed in the pipeline
- Dewatering will be accomplished at multiple locations coinciding with the low points of the alignment

Tunnel No. 2 Inspection

Tunnel No. 2 connects to Pipeline No. 1 and conveys water carried by the pipeline as well as water from the mid-level reservoir. This horseshoe-shaped tunnel extends from just upstream of the mid-level reservoir dam to the portal at the lower reservoir and is 14,650 feet in length. Tunnel No. 2 is lined through the entire length and is 6'-8" high by 6'-8" wide. The highest elevation of the tunnel invert is at the mid-level reservoir and the tunnel grade is constant toward the west at 0.125 percent downward to the lower level reservoir and from the high point at the mid-level reservoir a short section extends eastward to connect to the pipeline at a downward grade of 5 percent.

When the tunnel is not in operation it is expected that the entire tunnel drains by gravity to the lower level reservoir with the exception of the tunnel portion east of the midlevel reservoir which drains back into Pipeline No. 1. Ponding might be observed in localized areas where the invert has been scoured.

The tunnel has three major points of access:

- Mid-level reservoir dam gate shaft at Sta. 154+51
- Shaft A at Sta. 69+30
- Tunnel Outlet Portal at Sta. 13+50 (lower level reservoir)

Tunnel No. 2 has not been formally inspected, although the RWA reports that pre-1990, RWA personnel were able to walk the tunnel. Although the tunnel is functional, and no changes in its carrying capacity have been observed, there are some existing issues within the tunnel, like an area of high infiltration referred to as the “Carwash” by those individuals who had previously entered the tunnel, which will require attention. The tunnel is 75 years old (25 years older than Tunnel No. 1) and it is expected that the inspection will reveal the liner will not be in as good a condition as the lined portions of Tunnel No. 1. Only some minor changes are planned for inspection of Tunnel No. 2. These changes are minor in nature and include better video equipment, lighting and an increased ventilation requirement as prescribed by the RWA.

CONCLUSIONS

Many of the existing conveyance systems in the U.S. have reached and surpassed their original design life without formal assessment of their current condition. There may be some systems which have never been thoroughly inspected since they were put in service. Thorough condition assessments provide essential planning information for asset management programs. First-hand inspection provides the owner with greater detail than remote (e.g., camera) inspection and, when properly planned and executed, can be accomplished safely and at a cost comparable to the cost of remote inspection. These programs can greatly increase a municipality’s ability to provide reliable service, anticipate future fiscal demands, and meet customer expectations.