



Research
Tunnel Engineering—Article

Lake Mead Intake No. 3

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ABSTRACT

As a result of a sustained drought in the Southwestern United States, and in order to maintain existing water capacity in the Las Vegas Valley, the Southern Nevada Water Authority constructed a new deep-water intake (Intake No. 3) located in Lake Mead. The project included a 185 m deep shaft, 4.7 km tunnel under very difficult geological conditions, and marine works for a submerged intake. This paper presents the experience that was gained during the design and construction and the innovative solutions that were developed to handle the difficult conditions that were encountered during tunneling with a dual-mode slurry tunnel-boring machine (TBM) in up to 15 bar (1 bar = 10^5 Pa) pressure. Specific attention is given to the main challenges that were overcome during the TBM excavation, which included the mode of operation, face support pressures, pre-excavation grouting, and maintenance; to the construction of the intake, which involved deep underwater shaft excavation with blasting using shaped charges; to the construction of the innovative over 1200 t concrete-and-steel intake structure; to the placement of the intake structure in the underwater shaft; and to the docking and connection to an intake tunnel excavated by hybrid TBM.

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1. Introduction

The recently constructed Lake Mead Intake No. 3 project consists of a deep sub-aqueous tunnel, which was excavated with a dual-mode slurry tunnel-boring machine (TBM) at water pressures of up to 15 bar (1 bar = 10^5 Pa). The Lake Mead Intake No. 3 project [1] also included a submerged intake structure, the tunnel access shaft [2], and connections to an existing intake and water treatment facility.

The need for the new intake was driven by the declining levels of Lake Mead, which were caused by a prolonged drought. Lake Mead is the largest reservoir in the United States, measured by water capacity, and is located about 40 km from Las Vegas, Nevada. Formed by the Hoover Dam, Lake Mead is 180 km long when the lake is full and has a 640 km² surface area; when filled to capacity, it holds 32 km³ of water. The lake has not reached full capacity since 1983, however, due to a combination of drought and increased water demand. It is supplied by the Colorado River and is the largest human-made reservoir in the United States. Along with Lake Powell, Lake Mead serves 25 million people in seven states, including the residents of Las Vegas and Phoenix.

Prolonged drought conditions in the Southwestern United States have strained the lake, and it is currently only filled to about 42% of the full reservoir capacity. At its fullest in 1983, the level of the lake stood at 373 m above mean sea level (AMSL). In June 2016, the level stood at 327 m (1072 ft). The Southern Nevada Water Authority (SNWA) intakes in Lake Mead serve as the major water source for Las Vegas. The Lake Mead Intake No. 3 project will permit drawing lake water at much lower water elevations, when the existing Intake No. 1 and No. 2 projects would be unusable.

The project location is shown in Fig. 1 and the final layouts of the three intakes are shown in Fig. 2. Fig. 3 shows the effects of the drought on the lake.

In March 2008, SNWA awarded the Vegas Tunnel Constructors (VTC), a joint venture of Salini-Impregilo S.p.A and S.A. Healy Company, a \$447 million design-build contract for the major underground portion of this work. Arup Group Limited, supported by Brierley Associates Corporation, was the design engineer for VTC. The design-build contract included the 185 m deep tunnel access shaft, the 4.7 km long and 6.1 m diameter tunnel, and the submerged intake structure. Additional underground contracts involving shaft and connector tunnel excavation and pump station construction formed part of the overall project.

The following sections describe some of the most challenging aspects of this project.

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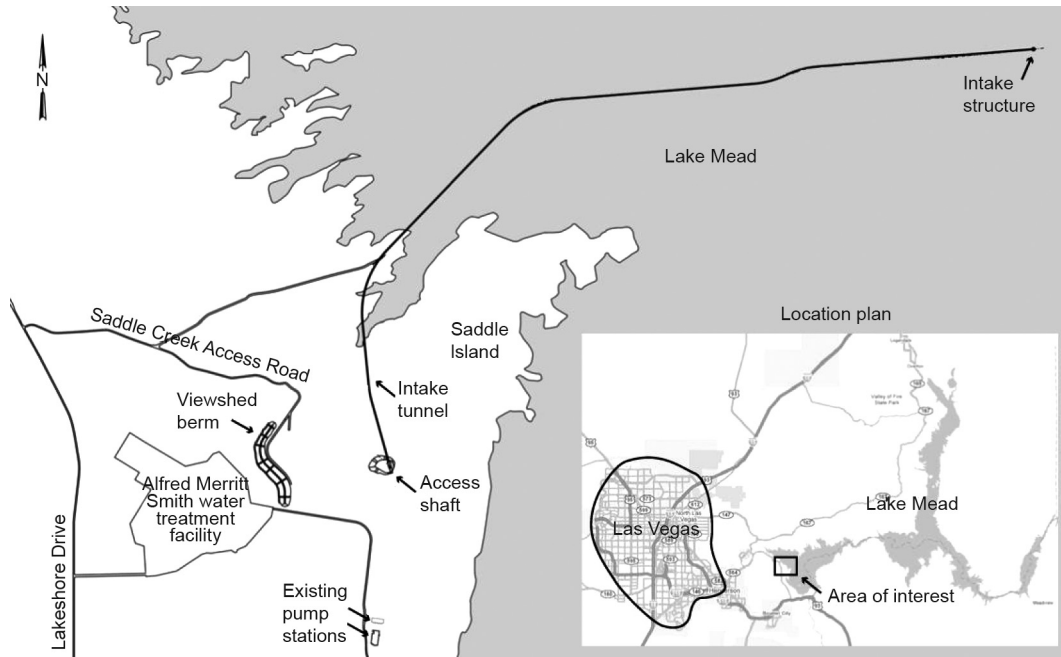


Fig. 1. Project location and layout.

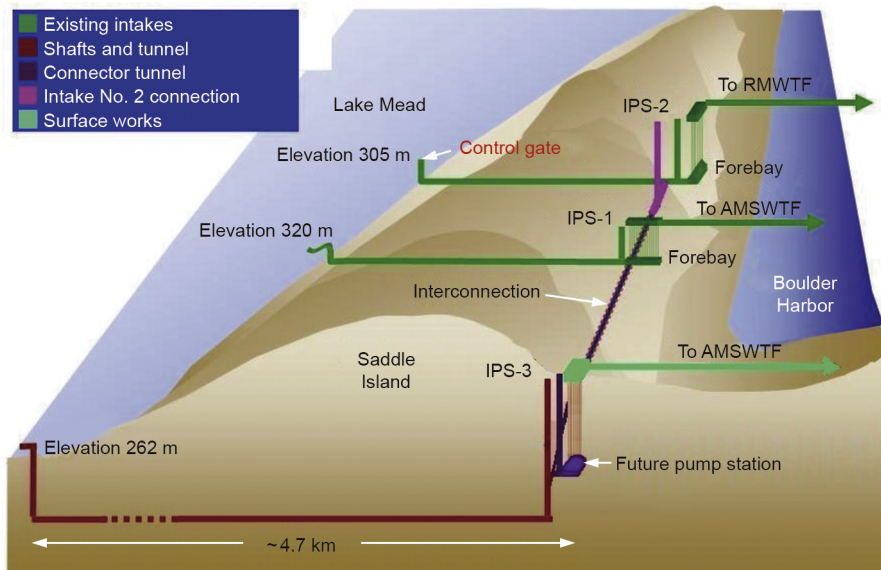


Fig. 2. Intake locations and connections to the SNWA water treatment facilities (RMWTF and AMSWTF). IPS: intake pump shaft.

2. Procurement

Given the unique nature of the contract, SNWA reviewed the procurement approach and selected a design-build procurement method [3]. This was primarily because the schedule savings of a design-build approach were best suited to SNWA’s need to achieve construction of Intake No. 3 in a timely manner. In addition, the design of a project is strongly related to the design-builder’s means and methods, so this approach places the responsibility for the design and construction on a single entity, the design-builder, who can apply creative design solutions to difficult construction challenges.

The procurement approach that was adopted included a two-stage selection process. Bidders that were selected to proceed to the second phase had the opportunity to meet with SNWA in con-

fidential meetings, which allowed constructive discussion on the contractual and technical approach to the project.

3. Risk management

Recognizing the relatively high levels of risk associated with the contract, most notably closed-face tunneling at 15 bar, SNWA adopted a proactive risk-management approach [4]. This approach included the identification of key issues early in the design process and the definition of a risk-management approach, which included:

- The provision of a geotechnical baseline report (GBR) as part of the contract documents;
- The adoption of the Code of Practice for Risk Management of Tunnel Works;

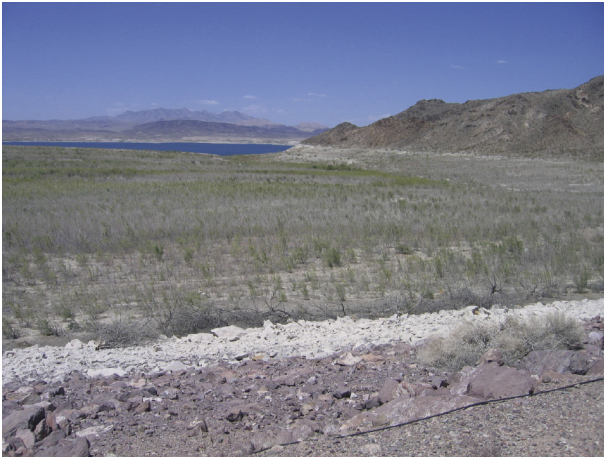


Fig. 3. View of Lake Mead; the area in the foreground was originally submerged, and the “bathtub ring” shows the original water level.

- The transfer of the SNWA risk register to VTC at the contract award; and
- A requirement for VTC to prepare a risk-management plan.

VTC actively engaged in the risk-management process and created a plan that included clear identification of responsible individuals, lines of communication, constructability reviews, and monitoring of the work. Risk identification and review meetings were held on a regular basis.

4. Geology

The ground along the alignment was characterized in terms of four major lithologic units—one Precambrian and three Tertiary units—with a number of subunits (Fig. 4). These units are as follows:

(1) **Saddle Island complex (P_c)**. The tunnel starts in stable Saddle Island lower plate (P_{cl}) metamorphic rocks with fair average rock-quality designation (RQD), and then passes through the detachment fault into stable Saddle Island upper plate (P_{cu}) metamorphic and volcanic rocks with poor average RQD. The detachment fault was 30–40 m thick at the tunnel horizon, and was short-term stable to unstable, with the potential for significant water inflows. It consisted of heterogeneous, crushed, and brecciated metamorphic and volcanic rocks with very poor to poor RQD. Rock strengths were up to 200 MPa in the Saddle Island complex.

(2) **Muddy creek formation (T_{mc})**. The majority of the tunnel was in the T_{mc} , a low-permeability sedimentary rock. Typical rock strengths in the muddy creek were 5–10 MPa and the rock mass permeability was low. The T_{mc} was subdivided into four units:

- T_{mc1} = Stable to short-term stable muddy creek gypsiferous mudstone;
- T_{mc2} = Stable to short-term stable muddy creek interbedded siltstone, sandstone, mudstone, and conglomerate that is weak with low toughness;

- T_{mc3} = Stable to short-term stable muddy creek conglomerate, ranging from very weak and uncemented to well-cemented; and
- T_{mc4} = Stable to short-term stable muddy creek conglomeratic breccia that is well indurated and well-cemented, with well-developed jointing.

(3) **Red sandstone unit (T_{rs})**. Approaching the intake, the tunnel passed through the T_{rs} , an unstable conglomeratic breccia that is weak and unindurated to poorly indurated (soil-like).

(4) **Calville Mesa (basalt) unit (T_{cm})**. The intake structure and a short length at the end of the tunnel were in the T_{cm} , a stable and blocky to very blocky and seamy, vesicular, and non-vesicular Calville Mesa basalt.

5. Tunneling

5.1. Dual-mode tunnel-boring machine

The TBM for the project (Fig. 5) was designed as a single-shield machine with capabilities to meet the range of challenges that were presented by the difficult hard rock ground conditions, potential for high groundwater inflows, and weak sedimentary rock under high hydrostatic pressures. It was anticipated that several sections of the tunnel, those with the more permeable rock, would require closed-faced excavation; that some lengths in the relatively impermeable sedimentary rock would be excavated in open mode; and that pre-excitation grouting would potentially be needed in some areas for excavation or maintenance stops. Therefore, VTC procured a fully shielded TBM that possessed the ability to operate in both pressurized and open modes and that could tunnel through rock, soil, and mixed-face conditions.

Particular attention was paid to probing and ground improvement ahead of the TBM, and the design allowed for 14 periphery and up to 30 face-drilling portals in order to provide a good range of hole locations. The machine was equipped with two drill rigs permanently located within the shield to allow drilling through the face, and a further permanent drill rig was situated behind the segment erection area to allow drilling through the periphery drilling ports in the TBM. Provision was also made for a fourth rig to be temporarily fixed on the segment erector. Drilling and probing were possible in all positions in open mode, and blow-out preventer units could be added to the majority of the holes to allow drilling in closed mode as well. Two grout plants were located on the back-up gantries, completed with silos, pumps, and mixers.

To deal with the risk of a sudden water inflow in open mode, a central horizontal screw conveyor was provided to remove muck from the face, rather than the more conventional conveyor found on rock machines. This allowed rapid closure of the gate within 120 s. In situations in which the rock face was unstable or groundwater inflows were excessive, a semi-closed or full-pressurized closed mode could be used with excavated spoil handling via a fully closed slurry circuit. Hyperbaric facilities were provided to allow access to the cutterhead chamber, with up to 17 bar of external water pressure.

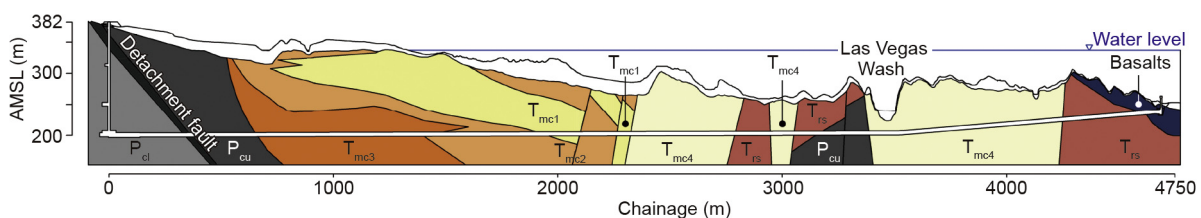


Fig. 4. Tunnel geology.

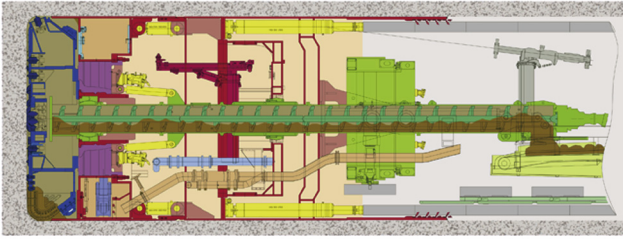


Fig. 5. TBM configuration (open-mode operation shown).

In closed-mode operation, the machine operated in full slurry mode, using a pressurized air bubble for control of the face pressure. It was possible to operate in closed mode at a lower pressure than the full external water in zones of stable and lower permeability rock. It was possible to estimate the extent of groundwater inflow during this type of closed-mode operation by monitoring the slurry concentration around the circuit. In open mode, the excavated material was removed by means of the horizontally arranged screw conveyor through the ring build area and onto a belt conveyor.

A change of operation mode did not require modification at the cutterhead. Closure of the rear discharge gate of the screw conveyor resulted in the excavation chamber being isolated, creating a closed system. The section of the screw casing within the cutterhead area was then hydraulically retracted before the slurry circuit was activated.

The TBM was equipped with a rock crusher and a submerged wall gate in front of the intake to the slurry system (suction grill). The closed system was completed with pipe-works and pumps on the trailing gear, along the tunnel, up the shaft, and over the above-ground treatment and slurry plant.

Some of the key features of the TBM are included in Table 1.

The tunneling system was designed and equipped for hyperbaric-face human entry. A standby decompression chamber equipped with an oxygen decompression system was permanently located behind the ring build area. The standby decompression chamber was large enough for extended decompression times, including the complete decompression process if required. The chamber was designed to accommodate the use of mixed-gas breathing systems (trimix or heliox) for higher chamber pressures.

Table 1
TBM technical data.

	Technical data
Machine type	Dual-mode mixshield
Manufacturer	Herrenknecht AG
Excavation diameter	7.22 m
Length	190 m
Total weight	1450 t
Total power	5750 kW
Cutterhead	Hard rock, dual mode
Cutters	17 in backloading
Total power supply to the TBM	2800 kW
Torque	10.1 MN·m (11.7 MN·m in high-pressure mode)
Shield diameter	7.18 m
Maximum pressure	18 bar
Thrust	70 000 kN (100 000 kN in high-pressure mode)
Mucking open mode	690 t·h ⁻¹ (continuous conveyor in tunnel)
Mucking closed mode	1100 m ³ ·h ⁻¹ , rock crusher (slurry treatment plant at portal)
Backfilling system	Mortar or two-component
Drainage system	400 m ³ ·h ⁻¹ onboard treatment plant
Probing/grouting	3 permanent drills, 1 temporary erector-mounted drill, 14 periphery positions
Drill pattern	30 face positions
Trailing gear	15 back-up gantries, closed deck, train supply

For extensive work under high pressure, a shuttle was purchased (but never used) that would have allowed transfer of the crew between the airlock and a hyperbaric habitat at the bottom of the access shaft. An access tube was fabricated that would have been installed to provide a connection from the standby decompression chamber to a docking point with a hyperbaric transportation shuttle at the rear of the shield.

5.2. Tunnel lining

The 6.1 m inner diameter (ID) segmental lining was designed as a universal tapered ring capable of withstanding full hydrostatic pressure of 17 bar for a 100-year design life. Each segment ring consists of four rhomboidal segments, a trapezoidal counter key, and a key. The relatively high segment length of 1.8 m was chosen to reduce the number of joints along the tunnel. In comparison with 1.5 m long segments, the 1.8 m segment length reduces the total joint length by 12%. The 356 mm thick segments were formed from C40/50 concrete and conventionally reinforced with a welded wire cage of 52 MN·m⁻² (75 ksi) steel. Spear bolts were provided on both radial joints (together with guide rods to provide good build) and on the circumferential joints (with ball joints). An ethylene-propylene-diene monomer (EPDM) rubber gasket, rated to 38 bar, was also provided.

The segment ring was provided with a taper of 51 mm, and the segment ring could be rotated in 16 different positions. The taper was arranged such that the key was on the widest portion of the ring, and allowed an absolute minimum turning radius of 220 m. To limit the occurrence of cruciform joints, which are more difficult to seal against external pressure, certain orientations on adjacent rings were avoided wherever possible; consequently, the minimum radius was around 275 m.

5.3. Water inflow tests

In order to access the working chamber under atmospheric pressure, water inflow needed to be allowed at the tunnel face; thus, it was important to estimate in advance the rate of water inflow. This was done by lowering the face support pressure in steps of 0.5 bar. After each step, the increase in water inflow was measured by observing the change of water outflow in the slurry line while keeping the slurry level in the bubble chamber constant. Steady flow conditions were normally obtained in 15–20 min. After several steps (generally more than 10), the relationship between the quantity of water inflow and the face support pressure could be established and subsequently extrapolated to 0 bar. This approach allowed the safe estimation of the quantity of water inflow under atmospheric conditions—that is, the approach allowed estimation to be performed without risking a face instability associated with lowering the support pressure to 0 bar.

During the water inflow tests, the force acting on the cutterhead, the torque (by rotating the cutterhead without TBM advance), and the color of the drained water were observed in order to identify the possible onset of local instabilities in a timely manner, and thus interrupt the test by immediately increasing the support pressure to its initial value.

5.4. Tunneling through the Saddle Island upper plate

An extensive review of the face stability was performed for the anticipated range of ground conditions, hydrostatic head, and permeabilities [5,6]. It was concluded that within these ranges, much of the alignment fell into the geotechnically demanding intermediate area between “drained” conditions and “undrained” conditions, and it could not be determined for certain whether the more stable short-term conditions or unfavorable long-term

conditions would occur. This conclusion made the determination of the operational approach for the TBM in advance of excavation more complex. A tunneling plan was developed based on a qualitative review of the data for the expected conditions, but with a contingency case for worst-case conditions, in which advance drainage in the sedimentary materials would increase face stability and reduce the requirements for applied pressure by up to 10 bar.

In practice, the most challenging section of tunneling was the initial section through the highly permeable Saddle Island upper plate formation, which had less stable face conditions and higher water inflows than predicted. After launching on 27 December 2011, the TBM advanced in closed mode for 140 m, with face pressures up to 7 bar prior to entering this formation. The TBM continued to work in closed mode with pressures up to 13 bar. Penetration rates dropped significantly approaching 280 m, where the machine stopped for maintenance. A water inflow test was performed to see if an intervention could be carried out in free air, but with the pressure only reduced to 10 bar, the water inflow was over $200 \text{ m}^3 \cdot \text{h}^{-1}$. As a camera inspection of the cutterhead showed no excessive levels of wear, progress was resumed with higher face pressures of up to 15 bar being used. Penetration rates improved for a while, but then decreased when approaching station 430 m. At this point, damage to the TBM cutterhead was detected and it was decided that maintenance was needed.

5.5. Pre-excavation grouting

A major campaign of pre-excavation grouting was performed after 430 m of tunneling, when cutterhead wear was detected. Three overlapping canopies were grouted using over 560 m^3 of grout [7].

The ground treatment ahead of the machine was planned and based on the grouting intensity number (GIN) method [8]. Maximum injection pressure and maximum injection volume were defined in accordance with the fractured ground conditions. A significant difficulty was caused by the fixed pattern of available drilling holes through the cutterhead. For different stages, a methodical injection sequence was followed for the primary and secondary holes.

Working at 13 bar of face pressure meant that normal drilling and grouting procedures were not applicable. It was very difficult to manage the water inflow (with pressure) and to place the packer once the hole was drilled. In order to keep up with the challenging geological conditions, some modifications and innovations of the equipment were introduced. In particular, the focus was on the following:

- Designing an additional backflow preventer to be installed in front of the original one, in order to prevent water and materials coming into the tunnel;
- Changing the geometry of the drill steels from a T38 with a round shoulder to a T38 with a square shoulder, in order to reduce the friction point between the steel and the inner rubber of the backflow preventer;
- Designing a packer and the casing in-house, in order to be able to install the packer in highly fractured material, where the casing allowed the installation of the packer at the correct location and inflation without damaging the backflow packer;
- Using different sizes and configurations of drilling bits; and
- Using different mix designs depending on the fractured rock mass, with both Portland and microfine cement being used.

After completion of the third canopy, it was possible to gradually reduce the face pressure to atmospheric conditions and perform critical face maintenance, despite a water inflow of 220

$\text{m}^3 \cdot \text{h}^{-1}$. Maintenance included the replacement of worn pipelines, valves, and pumps, and the installation of a new hydraulic valve on the slurry return line.

When the slurry circuit maintenance was completed, the TBM advanced forward so that the unstable area was behind the TBM shield. However, after progressing 20 m, some steel fragments were found on the magnet at the slurry separation plant. It was decided to stop the TBM from advancing in order to investigate the problem. The pressure was successfully lowered to atmospheric level, and the face inspection showed that the central part of the cutterhead had severe damage to the cutters and the cutter housing. The water inflow was measured to be approximately $900 \text{ m}^3 \cdot \text{h}^{-1}$, but the rock condition was stable; therefore, maintenance work was started. A niche was excavated in front of the cutterhead using small hand tools. Once the excavation was completed, the structural repair to the cutterhead was performed. The water had to be panned away from the work area and ventilation had to be established for the cutterhead repair (Fig. 6). Technicians from the TBM manufacturer were brought to the site to oversee the repair. The central section of the TBM had to be repaired completely, including the disc cutter housings, structure, wear plates, and cutters.

5.6. Remaining length of the tunnel drive

Performance was much better in the areas of sedimentary rock, and advance drainage was not needed to maintain face stability [9]. The TBM was operated in open and closed modes through this section depending on the ground conditions encountered. The first 1615 m of excavation was completed in 6 months, averaging approximately $14 \text{ m} \cdot \text{d}^{-1}$. The main challenges in this stretch were muck-handling issues with the conveyor belt and clogging of the cutterhead, particularly in the areas where the clay content was high and the TBM was advancing in closed mode while applying high pressure at the face.

After this section, some significant TBM repairs were undertaken, including replacement of the sealing system (which required removal of the cutterhead) and replacement of all pinion gears.

6. Intake

6.1. Construction of the intake structure

In addition to the high-pressure tunneling, constructing the intake structure and making the connection to the tunnel were highly challenging activities due to the quality of the rock and a water depth of over 100 m [10]. During the bid design process, a conventional drilled shaft, or dry tap, arrangement was considered. This consisted of the placement of a 5 m diameter steel riser shaft into the lake bed. The tunnel would be bored under the riser, and a connection would be made by excavating between the tunnel and the riser. Before the tunnel arrived at the intake location, this would require a sequence of ground improvement, drilling a large-diameter shaft, and placing a riser shaft and grouting.

Recognizing the risks, the VTC team looked at alternative configurations and construction methods. The chosen solution, shown in Fig. 7, was to utilize an intake structure that could be fabricated close to the shore and then be prepositioned into the lake bed using immersed tube techniques; this structure would serve as a location in which to “dock” the TBM at the end of the drive. Once the TBM entered the intake structure, and a seal was made between the TBM skin and the structure through grouting (or freezing if necessary), the TBM could be partially dismantled and a final concrete lining could be placed. For the bid, a steel structure



Fig. 6. Cutterhead repair.

was designed; however, a concrete-and-steel hybrid option was developed after the contract award.

The intake structure itself was over 1200 t and was constructed while being supported entirely by a floating barge close to the shore. This barge needed to be capable of supporting the weight during the construction of the intake, and needed to be able to lower the intake in place when needed. The lowering was done by strand jacks mounted on a large structural steel structure mounted on the barge.

The intake structure had two main sections: the high-pressure section made from concrete, and the low-pressure section made from stainless steel. The high-pressure section was made of heavily reinforced 55 MPa concrete and was the base portion of the intake, forming the TBM reception chamber; this required the section to be designed to resist the external water pressure when the inside of the chamber was at atmospheric pressure.

The low-pressure section of the intake was the upper portion, which was made entirely of 316L stainless steel. It consisted of 16 m of total stainless riser, which was comprised of 14 m of 4.8 m diameter riser pipe topped by a trash rack approximately 2 m high. The riser pipe's design varied in thickness: The first 2 m attached to the corbel embed were made of 30 mm stainless plate, the next 5 m were made of 25 mm plate, and the remainder of the riser was made from 20 mm plate.

A very specific blend of 316L stainless steel was chosen for the fabrication of the intake riser in order to ensure it could meet the

corrosion requirements over the 100-year design life. The intake's environment posed two main threats to the intake's materials: corrosion from high chlorine concentration from the chlorine-dosing line, and damage due to the high electroconductivity of the water in Lake Mead. In order to ensure the 316L stainless steel would last for 100 years in this environment, the material was required to have a minimum of 2.5% molybdenum (Mo) and low carbon in its chemical makeup. This meant that 316L stainless steel had to be used and that 2.5% Mo had to be specified in the chemistry, because 316L stainless steel can have between 2% and 3% Mo in the definition of steel grades in ASTM A240.

In order to complete the job, a plug had to be installed in the intake structure to allow the TBM to enter it without being flooded. In the future, this plug will also allow unwatering of the tunnel for inspection and maintenance. To perform this duty, a bulkhead was designed in the form of a stainless steel hemispherical cap fitted with a rubber gasket. The bulkhead was built so that it fitted inside the low-pressure section and came to rest on top of the corbel embed. A rubber gasket was attached to the bottom of the bulkhead with epoxy to create a seal between the two opposing stainless steel surfaces. The bulkhead was designed to withstand a maximum pressure of 13.5 bar and was tested to 20 bar.

6.2. Excavation for the intake structure

Creating an excavation for the intake structure was one of the most challenging aspects of the marine work. This task required the excavation of a total of nearly 37 000 m³ of material located 100 m under the surface of Lake Mead. The excavation area was determined by the size of the intake structure and the requirement for at least two tunnel liner rings within the concrete backfill zone. The material at the bottom of the lake was a mix of desert alluvial fan, vesicular and non-vesicular basalt, and small amounts of clay.

After the consideration of many options, an airlift system and crane/clam bucket combination was used for excavation. The decision regarding whether to use the airlift or clamshell system was mostly based on material composition. It was generally better to move finer material with the airlift and rockier, coarser material with the clamshell. Fine material had a tendency to fall through the clamshell bucket, and the airlift was often clogged when used

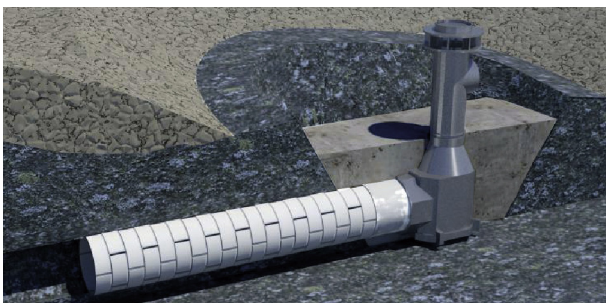


Fig. 7. A rendering of the intake structure.

to lift large rocks. Excavated material was placed on the lake bottom.

When hard rock was encountered, it was fractured with the use of shaped charges and then removed with either the airlift or clam-shell. Shaped charges were chosen for the marine blasting because they could be placed directly on the rock surface and detonated. Traditional blasting methods require drilling, the loading of an explosive, and then blasting. Shaped charges operate like a projectile: An explosive substance is positioned above an aluminum shell that is attached to a spacer, thus providing an adequate distance from the rock surface. The space between the rock surface and the charge is designed to allow the development of a slug created by the rapid melting of the aluminum plate when the charge is detonated. The slug basically works like a bullet or artillery projectile and is shot into the rock at high velocity. An air bubble curtain was used in this case to reduce the effects of the pressure wave created by the detonation.

As the excavation progressed, it was necessary to quantify the amount of material being removed. This was done with the use of a multi-beam sonar system. The multi-beam sonar system was mounted onto a dedicated vessel and used approximately once or twice a week depending on progress. It provided points in an X, Y, Z format that allowed cut-and-fill volumes to be calculated based on the difference between the pre-project survey and the most recent survey.

6.3. Intake placement

To facilitate the positioning of the intake structure, a heavy steel structure was used as a guiding and positioning frame for the intake. After the survey controls were satisfied, the frame was grouted in place using self-leveling tremie concrete to approximately 0.3 m below the top part of the frame. This tremie concrete operation was monitored with a remotely operated vehicle (ROV). A few days after concrete placement, the position and the elevation of the frame were resurveyed again to confirm the location.

Once the frame was securely in position, the intake structure was towed out into the lake, as shown in Fig. 8. It was positioned above the frame and then successfully lowered by the strand jacks onto the frame using guide wires. Lowering took place over a period of approximately 60 h. Once the intake structure was completely placed on the bottom frame, another manual measurement of position and elevation was taken to confirm the position, and then all lifting and guiding cables were removed. The final position of the intake structure was verified to be within the tolerance of the design specs. The maximum deviation in northings and eastings was a difference of 380 mm in the easting of the TBM reception chamber. This final position was fed into the guidance system of the TBM and a small alignment correction was made to the TBM approach alignment.

6.4. Tremie concrete placement

Approximately 9200 m³ of concrete was placed in a continuous pour over a 12-day period. The tremie pipe used was 250 mm in diameter and was fed by two identical concrete pumping and placing systems. Each system was capable of delivering approximately 92 m³·h⁻¹ at peak operation. The pumping systems were fed by barges loaded with eight concrete trucks each. Each truck had the capacity to carry 7.6 m³ of concrete. Loaded barges docked at the crane barge on an average of every 80 min. Concrete was placed at 42–46 m³·h⁻¹ when the operation was running without interruption.

The tremie pipe's position at the bottom was tracked by GPS. This allowed the concrete's profile to be graphically monitored on a computer monitor. The final elevations of the concrete were



Fig. 8. Intake structure being lowered into position.

checked with a long tape and confirmed with a multi-beam sonar survey.

More extensive details on the tremie concrete, including the design criteria and mix designs, are given in Ref. [11].

6.5. TBM hole-through

A core drill was performed 15 m from the intake structure in order to investigate the transition between the basalt and the tremie concrete; this included looking at the quality of the tremie concrete and the interface at the intake “soft eye” location. As anticipated, the basalt was highly fractured due to the previous blasts of the intake structure. The quality of the tremie concrete was better than expected and the results of the core drill showed a clear joint between the tremie concrete and the intake structure.

The TBM parameters were adjusted to reduce the rate of advance through the tremie concrete and the fiberglass reinforcement of the soft eye. This procedure reduced potential damage to the intake structure.

The excavating pressure was set at 9.3 bar during the final drive of the TBM into the intake structure; this matched the theoretical lake pressure.

The material from the soft eye during the last stage of the excavation was inspected at the separation plant. The concrete on the intake structure/soft eye/intake had been previously painted, and this was seen at the separation plant, indicating that the TBM was in the correct location. The TBM then continued to push forward until the shield stopped in line with an annular steel ring cast in the intake structure. After the installation of the bulkhead, the intake chamber was slowly unwatered.

After the breakthrough, it was planned that the annular gap between the shield and the intake structure would initially be sealed by injecting a quick-setting cement-based grout or a water-reactive chemical grout through the injection ports located around the perimeter of the front shield of the TBM. If these injections were not effective (i.e., no increase in grouting pressure during injection operation), the injection operations were to be stopped and the procedure would be replaced by a freezing solution. The TBM was equipped with a freezing jacket around the front shield that was capable of freezing the water remaining in the annular gap between the shield and the intake structure. However, after accessing the intake structure, the shunt flow around the TBM shield was measured to be under 1 L·s⁻¹, and there was no water leakage from the intake structure/bulkhead; as a result, no grouting was required.

In addition to successfully making a seal between the TBM and the intake structure, the connection was a complete success in

terms of the survey and the TBM alignment, with the TBM being within a tolerance of ± 3 mm of the required position.

Once the intake chamber was safely sealed, the disassembly of the cutterhead began, using lifting beams incorporated into the intake structure. Next, steel plates equipped with valves were welded between the TBM shield and the embedded entrance ring of the intake structure. The annular gap between the shield and the intake structure was grouted to provide a positive long-term seal, as the TBM shield was left in place. The final disassembly and removal of the internal sections of the TBM were then performed, with the final lining in this section being shotcreted in place.

7. Conclusions

The Lake Mead Intake No. 3 project was a very technically challenging and demanding project; it would not have been completed without the dedication and commitment of Salini-Impregilo S.p.A and S.A. Healy Company, Arup Group Limited, and SNWA working together in a true partnership. Many achievements were accomplished during the project, including the first time a TBM has been advanced at a face pressure of 15 bar.

Compliance with ethics guidelines

Jon Hurt and Claudio Cimiotti declare that they have no conflict of interest or financial conflicts to disclose.

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