1. Introduction

The new Intake No.3 at Lake Mead requires a deep sub-aqueous tunnel, to be excavated with a dual-mode TBM at anticipated water pressures of up to 17 bar. The Intake No. 3 project also includes a submerged intake structure, the tunnel access shaft and connections to an existing intake and water treatment facility.

The need for the new intake is driven by the declining levels of Lake Mead caused by a prolonged drought. Created by the construction of Hoover Dam in the 1930s, the 180 km Lake Mead lies on the Nevada-Arizona border about 50km southeast of Las Vegas. It is supplied by the Colorado River and is the largest man-made reservoir in the U.S. Along with Lake Powell, it serves 25 million people in seven states, including the residents of Las Vegas and Phoenix. Prolonged drought conditions in the U.S. Southwest have strained the lake and it is currently only filled to around 42 percent of the full reservoir capacity. At its fullest in 1983 the level of the lake stood at 373 m (1224 ft) above mean sea level (amsl). In November 2009 the level stood at 333 m (1093 ft). The Southern Nevada Water Authority (SNWA) Intakes in Lake Mead serve as the major water source for Las Vegas. Intake No. 3 will permit drawing lake water at elevations as low as 305 m (1000 ft) amsl — a level at which existing Intake No.1 would be unusable. The project location is shown in Figure 1 and the final layout of the three intakes in Figure 2.
In March 2008 SNWA awarded Vegas Tunnel Constructors (VTC), a joint venture of Impregilo SpA and SA Healy a $447m Design-Build contract for the major underground portion of this work (Contract 070F 01 C1). Arup, supported by Brierley Associates, is the Design Engineer for VTC. The Design-Build contract includes a 185 m deep tunnel access shaft, a 4.7 km long, 6.1 m diameter tunnel and a submerged intake structure. Two additional underground contracts, involving shaft and connector tunnel excavation, are also under construction.

This paper will describe the design and construction on the Design-Build contract. The shaft has been sunk using drill-and-blast methods with extensive pre-excavation grouting for water control, and with the final lining placed as excavation proceeded. The design features of the TBM will be described, together with an overview of the anticipated challenges during tunnel excavation. Construction of the intake structure will also be addressed.

2. Access Shaft and Cavern

The 9.1 m internal diameter Tunnel Access Shaft extends 185 m below the final ground elevation. At the bottom of the shaft a 60 m long, 14 m wide by 10.5 m high cavern will be excavated to allow launching and operation of the TBM.

Approximately one-third of the way up the shaft, a short 26 m length of 6m wide by 6m high horseshoe configuration stub tunnel is being constructed, known as the IPS-3 Stub Tunnel, which will connect with the adjacent underground connection tunnel being built under a separate contract. During construction, this stub tunnel will be used to house pumps for the slurry circuit and groundwater discharge system. Another, slightly smaller stub tunnel is being constructed a further one-third of the way up the shaft to also house slurry and water pumps, such that the head on each lift of the pumps is limited to around 70 m.

2.1 Shaft and Cavern Geology

The shaft is constructed entirely within the Pre-Cambrian Saddle Island Formation. For the upper 20m, the shaft is in the Saddle Island Upper Plate, which consists primarily of blocky, seamy, slightly weathered to highly weathered-decomposed, very weak to strong Tertiary volcanic intrusive rocks, including dacite and basalt along with some pegmatite. Below the Upper Plate is the Detachment Fault, a 25 m thick zone where up to 75% of the rock profile is highly weathered to decomposed, or intensely fractured to crushed. Non-faulted rock in this zone comprises approximately 90% highly fractured Upper Plate rocks (basalt/dacite), and about 10% of strongly foliated chlorite phyllonite rock, most likely derived from the underlying Lower Plate amphibolite rock.
The remainder of the shaft is in the Saddle Island Lower Plate, which is predominantly amphibolite gneiss with occasional interlayers of amphibolite schist/biotite-chlorite schist/pegmatite. There are a number of significant shear zones in the Lower Plate, which vary in width between 0.6 and 3 m.

2.2 Shaft Excavation

Excavation of the shaft has been by means of drill-and-blast. A three-boom Tamrock shaft jumbo was used to drill blast holes and a Cat 939 track loader to fill 6 m³ sinking buckets. Initially, hoisting was accomplished with a 180 tonne Link Belt crane. Later, a 26 m tall headframe (Fig 3) was erected over the shaft to service the work. The work was supported with an Ingersoll-Rand double drum main hoist with 1250 hp, 36 tonne single line pull, and maximum rope speed of 245 m per minute. This hoist will also support the tunnel excavation. In addition to the double drum main hoist, four New Era stage winches, with 22.5 tonne line pull, were installed to support and hoist the work decks and concrete forms and to provide guides for the skips and buckets. A two-deck Galloway was suspended just above the working face to support all shaft activities (Fig 4).

Figure 3: Headframe and winch house

Figure 4: View up the shaft, showing Galloway and top of form and drill jumbo.

A typical shaft excavation round was 3 m deep, with an average of 150 drill holes and about 270 kg of powder. Because of the placement of the shaft jumbo, a V-cut was drilled for the center zone. Nonel detonators were used in all cases. ANFO was used above the water table, and stick powder was used below the water table.

The groundwater table at the Access Shaft is directly related to the lake level in Lake Mead. Consequently, at the time of construction, the lake level was approximately 150 m above the bottom of the shaft. As a result of the Detachment Fault and the shear zones in the Lower Plate, high water inflows were anticipated. To reduce these inflows, a program of probe drilling and pre-excavation grouting was required. The grouting program was based on a 36 m deep grout curtain, with 9 m of overlap, in order to obtain an approximately 3 m thick curtain around the shaft. Initially, primary holes were spaced at approximately 1.25 m centers around the perimeter of the shaft, looking out at 5 degrees. Secondary holes were spaced between the primary holes, looking out at 2 degrees. Three meter long standpipes were drilled and grouted in place at the drilling elevation. These were then fitted with valves and gages. Primary grout holes were drilled to a certain stage depth, and then pressure grouted. They were then redrilled and, if the results were satisfactory, deepened to the next elevation. When the primary holes did not return the desired result, secondary holes were drilled and grouted as well. Grouting continued in this manner until the 36 m depth was reached. Four interior probe holes were then drilled to verify the results.
The grout mix depended on the ground conditions as well as the results, and evolved as the shaft was extended. Cementitious materials included Type II/V cement, Type III cement, and ultrafine cements. As the program progressed, hole spacing between ground holes and stage depth were increased, and the criteria for refusal was refined as a function of achieved pressure and/or injection volume.

VTC selected the top down approach for the concrete lining to provide early permanent support and an increased ability to control groundwater inflows. A blast-proof shaft form with nominal height of 3 m was used, configured with a 1 m curb ring and a main section of 2.25 m. The curb ring was suspended from the previous placement by means of all-thread bars. Scribing pins and steel mesh were used to form the bottom of the curb. Concrete was then placed into the curb ring. While that was setting, the rest of the form was lowered, set, and poured. Generally there was less than 6m of excavated shaft below the most recent concrete placement. This minimized exposure and allowed enough room for the jumbo to drill the perimeter holes beneath the lining above. Contact grouting was performed after the concrete reached its design strength (Fig 5).

1.3 Cavern Excavation

The cavern and TBM starter tunnel construction are being carried out with a heading and bench excavation. From an initial shaft enlargement, a two-boom drill jumbo was used to create a 210-hole drill pattern in each face. The cavern extends from the shaft in both directions, and both faces were shot simultaneously (Fig 6).

In the cavern, TBM starter tunnel and the shaft stub tunnels, the support is required to achieve the 100-year design life. For this, a system of fiberglass rockbolts and steel fiber reinforced shotcrete has been designed that can be placed during the excavation. A series of drain holes are included to reduce any water pressure on the lining in the event that the tunnel is dewatered in the future for inspection or maintenance. A structural concrete invert is also placed in each area.

Figure 5: Access Shaft    Figure 6: Excavation of cavern top heading

2. Intake Tunnel

The Intake Tunnel consists of an approximately 4.7 km long tunnel beneath Lake Mead excavated with a TBM. The Intake Tunnel connects the Access Shaft at Saddle Island to the Intake Structure in the lake. The internal diameter of the tunnel will be 6.1 m, and the lining will be formed from a 356 mm thick precast concrete gasketed segmental lining. The tunnel will slope up from the Tunnel Access shaft, initially at a 0.1% gradient, and then at a 3% gradient once the tunnel has crossed beneath the Las Vegas Wash.
2.1 Geology

The GDR and GBR characterize the ground that will be encountered in the Intake Tunnel in terms of four major lithologic units, one Precambrian and three Tertiary units, with a number of subunits (Fig 7). These units are:

- **Saddle Island Complex (Pc):** The tunnel starts in the stable Saddle Island Lower Plate metamorphic rocks, with fair average RQD, and passes through the detachment fault into stable Upper Plate metamorphic and volcanic rocks with poor average RQD. The detachment fault is around 30 to 40 m thick at the tunnel horizon, short-term stable to unstable with the potential for significant water inflows and consists of heterogeneous, crushed and brecciated metamorphic and volcanic rocks with very poor to poor RQD. Rock strengths are up to 200 MPa in the Saddle Island Complex.

- **The majority of the tunnel is in the Muddy Creek Formation (Tmc), a low permeability sedimentary rock.** Typical rock strengths in the Muddy Creek are 5 to 10 MPa and rock mass permeability is low. The Muddy Creek Formation is subdivided into four units:
  - Tmc1 = Stable to short-term stable Muddy Creek gypsiferous mudstone.
  - Tmc2 = Stable to short-term stable Muddy Creek interbedded siltstone, sandstone, mudstone and conglomerate that is weak with low toughness.
  - Tmc3 = Stable to short-term stable Muddy Creek conglomerate, ranging from very weak and uncemented to well-cemented.
  - Tmc4 = Stable to short-term stable Muddy Creek conglomeratic breccia that is well indurated and well cemented, with well developed jointing.

- **Approaching the intake, the tunnel passes through the Red Sandstone Unit (Trs), an unstable “Red Sandstone” conglomeratic breccia that is weak and unindurated to poorly indurated (soil-like).**

- **The intake structure and a short length at the end of the tunnel is in the Calville Mesa (Basalt) Unit (Tcm), a stable, blocky to very blocky and seamy, vesicular and nonvesicular Calville Mesa Basalt.**

2.2 Dual-mode TBM

The TBM for the project has been designed as a single shield machine with capabilities to meet the range of challenges presented by difficult hard rock ground conditions, the potential for high groundwater inflows, and weak sedimentary rock under high hydrostatic pressures. The Geotechnical Baseline Report (GBR) identifies at least two tunnel reaches that would require “pressurized face excavation, extensive pre-excavation grouting and ground treatment, or a combination thereof”. To address these conditions, VTC required a fully shielded TBM with the
ability to operate in both pressurized and open modes and which 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 allows for 14 periphery and up to 30 face drilling portals to provide a good range of hole locations. To deal with the risk of a sudden water inflow in open mode, a central, horizontal screw conveyor is provided to remove muck from the face rather than the more conventional conveyor found on rock machines. This allows rapid closure of the gate within 120 seconds. In situations where the rock face is unstable or ground water inflows are excessive, semi-closed or full pressurized closed-mode can be used with muck transported via a fully-closed slurry circuit. Hyperbaric facilities are provided to allow access to the cutterhead chamber under up to 17 bar (247psi) of hydrostatic water pressure.

The Lake Mead TBM design (Fig 8) is based on numerous applications of high pressure Herrenknecht Mixshields and, to some extent, the high-pressure, dual-mode, shielded rock TBM being used on the Hallandsås railway project in Sweden and the open-mode shielded rock TBMs with their extensive pre-excavation grouting capabilities and equipment that recently completed the Arrowhead water delivery tunnels in San Bernardino, California.

The general philosophy behind the planned TBM operations, both for excavation and face interventions, is to operate in open mode wherever possible, using ground treatment and/or dewatering/drainage ahead of the face as required.

Figure 8: TBM Configuration (Open Mode operation shown)

2.2.1 Open-mode operation

In open mode, buckets and muck channels in the cutterhead will feed excavated material on to the centre arranged muck hopper from where it will be extracted by the horizontally arranged screw conveyor through the ring build area. From the screw conveyor’s discharge, a belt conveyor transports the excavated muck along the complete back-up section to the tunnel’s continuous belt conveyor.

The ability to handle water-laden muck in open-mode operation is considered to be one of the key elements. A large settlement basin is located under the screw conveyor discharge area to collect water spillage. The basin is connected to a flushing circuit that includes a small treatment plant installed to the rear of the backup gantries. This onboard circuit treatment plant configuration ensures a permanent flow of flushing water to minimize the risk of fines settling out in the spillage basins and reduces the solids content in the discharge overflow water to be pumped out of the tunnel.

The machine is equipped with three permanently installed drill rigs, two of them located inside the shield for the face positions, a third located behind the ring erection area for the periphery positions, with a fourth rig capable of being temporarily installed on the erector. Probing and drilling ahead of the face can be accomplished in open mode and also in closed mode conditions for the majority of the positions using blow-out preventer units. Two identical pre-excavation grout plants, complete with pumps, mixers, and silos, are installed on the trailing gear.
2.2.2 Closed-mode operation

In closed-mode operation, the machine will operate in full slurry mode following the Mixshield principle with an air bubble for face pressure control. This system allows the machine to operate in closed conditions but with free adjustable face pressure depending on the in-situ requirements. Closed-mode operation but with reduced pressure (lower than full water head) is possible depending on the given face or ground conditions. The possibility for a water volume balance of the entire slurry circuit also allows a clear picture of water inflow quantity through the face during reduced pressure operation.

The change of operation mode does not require modification at the cutterhead. As soon as the rear discharge gate of the screw conveyor is closed the excavation chamber is isolated and the system is closed. Before restarting in closed mode the screw casing is hydraulically retracted to clear the cutterhead center area and the slurry pumping circuit to the above-ground treatment plant is brought into operation.

The entire equipment and installation for the closed-mode slurry-pumping operation is permanently on board. The TBM is equipped with a submerged wall gate and a rock crusher in front of the suction grill and all the necessary pipework, pumps, compressed air and circuit installations in the TBM and along the trailing gear. The closed system is completed with slurry circuit installations along the tunnel, through the shaft and to the above ground treatment and slurry plant.

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

Table 1: TBM technical data

<table>
<thead>
<tr>
<th>Machine type</th>
<th>Dual mode Mixshield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Herrenknecht AG</td>
</tr>
<tr>
<td>Excavation diameter</td>
<td>7.22m</td>
</tr>
<tr>
<td>Length</td>
<td>190m</td>
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<tr>
<td>Total weight</td>
<td>1,450 tonne</td>
</tr>
<tr>
<td>Total power</td>
<td>5,750kW</td>
</tr>
<tr>
<td>Cutterhead</td>
<td>Hard rock, dual mode</td>
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<tr>
<td>Cutters</td>
<td>17in backloading</td>
</tr>
<tr>
<td>Power</td>
<td>2,800kW</td>
</tr>
<tr>
<td>Torque</td>
<td>10.1/11.7 MNm</td>
</tr>
<tr>
<td>Shield diameter</td>
<td>7.18m</td>
</tr>
<tr>
<td>Maximum pressure</td>
<td>18 bar</td>
</tr>
<tr>
<td>Thrust</td>
<td>70,000kN (100,000kN in high pressure mode)</td>
</tr>
<tr>
<td>Mucking open mode</td>
<td>690 tonne/hour (continuous conveyor in tunnel)</td>
</tr>
<tr>
<td>Mucking closed mode</td>
<td>1,100m³/h, rock crusher (slurry treatment plant at portal)</td>
</tr>
<tr>
<td>Backfilling system</td>
<td>Mortar or Two-component</td>
</tr>
<tr>
<td>Flushing system</td>
<td>400m³/h on board treatment plant</td>
</tr>
<tr>
<td>Probing/grouting</td>
<td>3 permanent drills, 1 temporary erector-mounted drill 14 periphery positions</td>
</tr>
<tr>
<td>Drill pattern</td>
<td>30 face positions</td>
</tr>
<tr>
<td>Trailing gear</td>
<td>15 trailers, closed deck, train supply</td>
</tr>
</tbody>
</table>

The tunneling system is fully prepared for hyperbaric face man-entry. A standby decompression chamber equipped with an oxygen decompression system is permanently located behind the ring build area. This chamber can be connected by an access tube to the rear shield bulkhead providing access to the drill chamber behind the front shield bulkhead. The size of the decompression chamber is large enough to allow for extended decompression times and to perform the complete decompression process. In addition, the system is prepared for the use of mixed gas breathing systems for higher chamber pressures. The breathing gas mixtures can be
Trimix or Heliox. For extended chamber time under high pressure, the tunneling system is prepared for a shuttle transfer of the crew between the airlock and a hyperbaric habitat at the bottom of the access shaft.

2.3 Tunnel Lining

The 6.1m ID segmental lining has been designed as a universal tapered ring capable of withstanding full hydrostatic pressure of 17 bars for 100-year design life. Each segment ring consists of four rhomboidal segments, a trapezoidal counterkey, and a key. The relatively high segment length/ID ratio of 0.3 was chosen to reduce the number of joints along the tunnel. In comparison with 1.5 m long segments, the 1.8m segment length reduces the total joint length by 12%. The 356mm thick segments are formed from C40/50 concrete and conventionally reinforced with a welded wire cage of 52 kN/m² (75ksi) steel. Spear bolts are provided on both radial joints (together with guide rods to provide good build) and on the circumferential joints (with ball joints). An EPDM gasket, rated to 38 bar, is also provided.

The segment ring is provided with a taper of 51 mm and the segment ring can be rotated in sixteen different positions. The taper is arranged such that the key is on the widest portion of the ring, and allows 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 will be avoided wherever possible, and consequently the minimum radius will be around 275 m.

3. Intake Structure

During the bid design process a conventional drilled shaft, or dry tap, arrangement was developed. This consisted of placement of a 5 m diameter steel riser shaft into the lake bed. The tunnel would be bored under the riser, and a connection made by hand-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 Figure 9, is 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, which would serve as a location in which to “dock” the TBM at the end of the drive. Once the TBM has entered the intake structure, and a seal made between the TBM skin and the structure through grouting, or freezing if necessary, the TBM can be partially dismantled and a final concrete lining placed. For the bid, a steel structure was designed, but a concrete and steel hybrid option has been developed since contract award.

![Figure 9: Intake Structure](image)

The authors acknowledge the permission of the Southern Nevada Water Authority to publish this paper.