

# High Cover TBM Tunneling in the Andes Mountains— A Comparative Study of Two Challenging Tunnel Projects in Chile

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## ABSTRACT

The Andes Mountain range is among the youngest and most complex in the world, geologically speaking. Tunneling projects, particularly for hydroelectric and water transfer schemes, are not new to the range but their past history has met with mixed success. Two new projects utilizing very different tunnel boring machines and excavation strategies are now providing a testing ground for modern underground construction equipment in the Chilean Andes.

This paper will analyze two projects: the Alto Maipo and Los Condores Hydroelectric Projects, located approximately 100 km apart in the Andes Mountains. The two strategies being employed will be analyzed in detail, as one project is using an open-type Main Beam TBM plus extensive ground support, while the other is utilizing a Double Shield TBM and segmental lining. The authors will look at TBM performance and ground conditions encountered in the two tunnels and what effects the TBM selection and ground support strategy may have had on each tunneling operation.

## ALTO MAIPO HYDROELECTRIC PROJECT

The Alto Maipo Hydroelectric Project for AES GENER and Luksic group is intended to channel the water of the main river that supplies water to the Santiago, the capital city of Chile. The project is located 70 km southeast of Santiago de Chile, in the municipal district of San Jose de Alto Maipo in the Metropolitan Area of Santiago at an altitude of 1025 to 2550 m.

The Inter-American Development Bank (IDB) signed a USD \$195 million loan agreement with Alto Maipo SPa, owned by AES Gener (60 percent) and Antofagasta Minerals (40 percent), as part of a financing package of more than \$1.2 billion for the Alto Maipo Hydroelectric Project. The project is co-financed by the International Finance Corporation, the U.S. Overseas Private Investment Corporation and six commercial banks. The total project cost will be roughly \$2 billion, 60 percent in the form of debt and the remaining 40 percent in equity.

In Santiago there are only two main rivers: one of them, the Mapocho River, is 80% fed by Maipo river waters. The project aims to channel the water of the main tributary streams of the Maipo River into a 70 km long tunnel. The project includes, among other things, five intakes; 67 km of tunnels excavated both by Drill & Blast and TBM with 800–1000 m of average overburden; two caverns—Alfalfal II and Las Lajas—with a combined capacity of 531 MW; and around 17 km of high voltage transmission lines.

The contract was awarded to two different joint ventures: Constructora Nuevo Maipo (CNM) and Strabag-Voigh Hydro. Constructora Nuevo Maipo S.p.A (CNM), a Joint

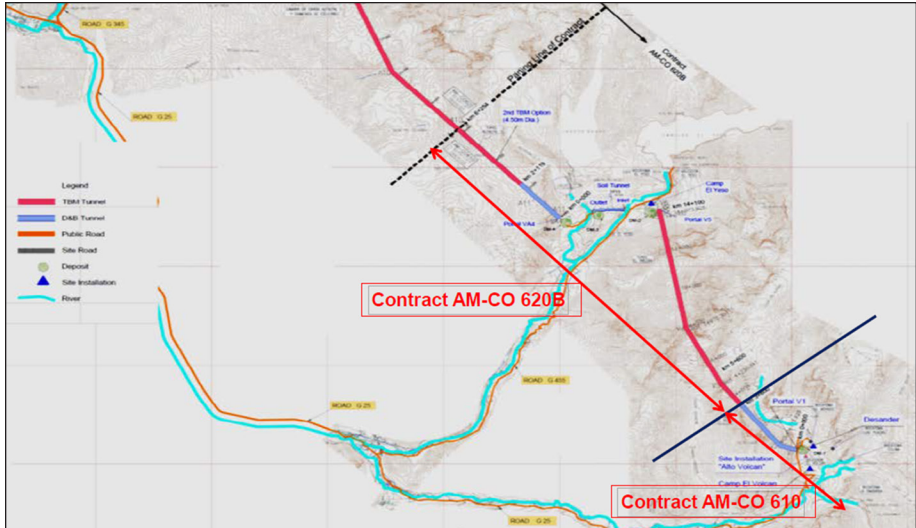


Figure 1. Map of project contracts

Venture between the companies HTCC-Hochtief Construcción Chilena Ltda—an affiliate company of the German firm Hochtief Solutions A.G.—and the Italian CMC-Cooperativa Muratori & Cementisti di Ravenna (CMC), is responsible for the execution of the works under the Contract AM-CO 610/620 at a cost of over USD \$280 million.

Figure 1 shows the portion of the project awarded to CNM including the following scope of works.

AM-CO610 Scope:

- Alto Volcan System
- El Volcan Tunnel System (upstream portion of El Volcan tunnel)

AM-CO620B Scope:

- El Volcan tunnel system (downstream portion of El Volcan tunnel)
- El Yeso Headrace System
- Alfalfal II System (Alfalfal II Headrace Tunnel, upstream section)

The project schedule foresaw the employment of one open-type hard rock TBM for boring part of the El Volcán Tunnel and part of the Alfalfal II Tunnel.

After being assembled at the portal next to the site installation called “El Yeso,” the plan was to have the TBM bore one 7 km section of the El Volcán Tunnel and, as an option, another 1,500 m beyond that point.

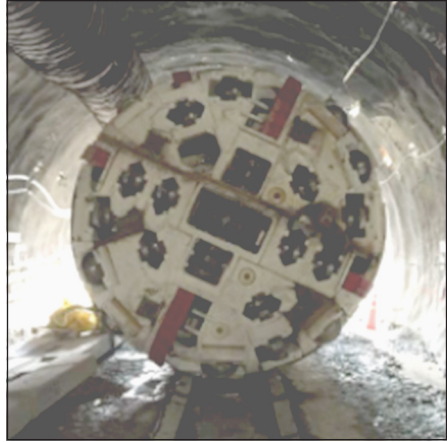
At the end of boring the El Volcán Tunnel, the TBM would be disassembled and transported through the bored and lined tunnel back to the portal “El Yeso,” and from there the machine would be moved to the portal of the Alfalfal II Tunnel.

The first section of the Alfalfal II Tunnel from station km 0 + 000 to km 3 + 250 was planned to be excavated by conventional methods—drill & blast. The second section from station km 3 + 250 to km 6 + 250 would be bored with the above TBM from

El Volcán Tunnel. The machine would be moved along the conventional bored tunnel section up to the underground face.

Disassembly and removal of the machine from the tunnel at the end of boring was planned to commence through the bored and lined tunnel back to the portal.

In January 2015 Robbins supplied a 4.13 m open gripper type hard rock TBM with back-up System and a Robbins Continuous Conveyor System for muck transport along the bored tunnel to the portal area (see Figure 2).



**Figure 2. Robbins first open gripper type Main Beam TBM inside El Volcán Tunnel**

The TBM with the back-up system and tunnel conveyor system were meant for boring El Volcán headrace tunnel and part of the Alfalfa II Tunnel, allowing quick access directly behind the cutterhead for the installation of extensive rock support measures such as rock bolts, steel mesh, ring beams and shotcrete.

### **Main Technical Features of the TBM for Rock Support**

The open type TBM supplied for excavation in hard rock was furnished with a hard rock cutterhead dressed with 17" Wedgelock™ back-loading cutters with 267 kN nominal load capacity each. For immediate support of the bored tunnel tube closest to the face, support shields on the roof and at the sides were provided as well as a vertical front support. Finger shields were attached to the roof support shield.

For primary rock support in the so-called L1 section, extending from the rear end of the support shields to the level of the TBM gripper assembly, two roof drills were provided as well as one probe drill, a ring beam erector, work platforms and stands and shotcrete application (see Figure 3).

The two (2) roof drills were assembled on a ring shaped support structure to allow for rock bolting service at the tunnel wall and at 106° on either side from the top crown position.

The probe drill was initially designed with a lookout angle of 5 degrees to the tunnel wall to allow for a conical pattern of drilled holes just outside the TBM bore excavation, so that the perimeter of the bored tunnel could be pre-grouted if necessary. The drill rig was attached to a ring shaped support carriage to allow for service around the circumference of the bored tunnel face and in dedicated spots of the face. The ring structure comprised a crown mounted segment which could rotate through 360 degrees. It was conceived to have one rig assembled at all times and to add another rig in case of need, which would be stored outside of the tunnel.

Under the protection of the support shields the ring beam erector allowed for installation of a full circle ring beam set or beam segments. A full circle ring beam was meant be pre-assembled in the erector and horizontally displaced for installation at the tunnel wall. Work platforms allowed the ground support to be installed under the personal protection of the roof shield finger support system.

As shown in Figure 4 and in lieu of the above traditional “finger shield,” the roof shield was designed to incorporate the Robbins-McNally “slat type” ground support system. The roof shield featured 35 roof “fingers” to protect the workers from rock falling in the TBM area. Each finger was installed in a pocket made of a structural angle bar and could be totally or partially removed when McNally rock supports were needed. The free pockets could then be used to install slats or rebar as needed for the McNally system.

One (1) additional roof drill and a shotcrete robot were supplied for secondary rock support in the so-called L2 working section, which follows the above L1 working section. The additional roof drill was assembled on a ring type positioner and allowed for roof bolting along the circumference of the bored tunnel wall except for the section covered by the invert segment.

With the robot operated via a remote control, two successive 150 mm thick layers of shotcrete could be applied for a total thickness of 300 mm along the circumference of the bored tunnel, except for the section covered by the invert segment.

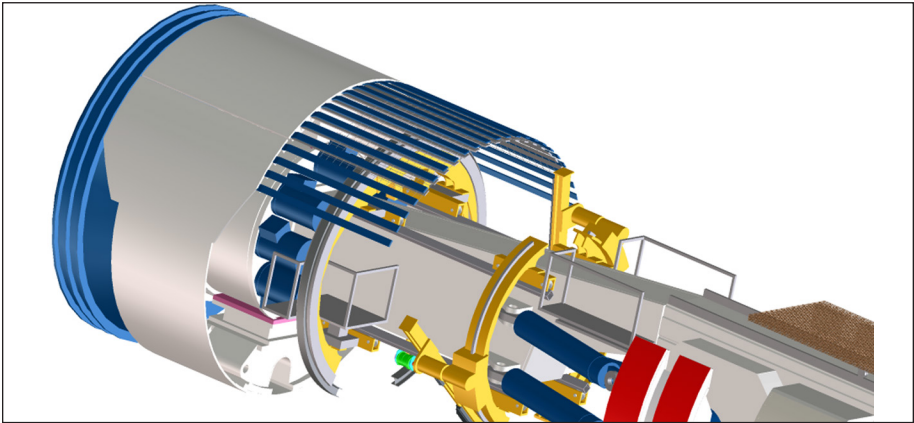


Figure 3. L1-working section ground support

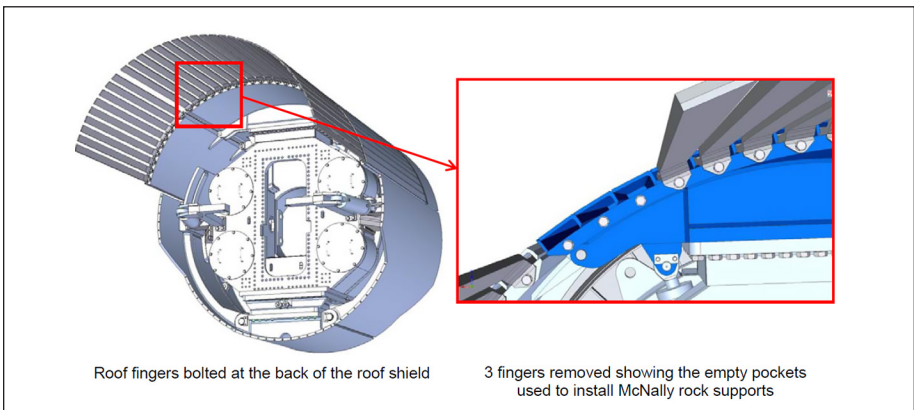


Figure 4. Finger shield removal and McNally System installation

Upon request by the project owner, a second open gripper type Main Beam TBM is being delivered at the time of preparation of this paper.

## Geology

The project was to be bored under a relative high overburden of up to 1,500 m at El Volcan tunnel in variable geology of the so-called “Abanico Formation,” ranging from competent andesite to andesitic breccias with some sandstone and tuff sections and some fault zones. In general, these rocks showed a good or fair geotechnical rock quality; however, in some highly altered tuffaceous sections the geotechnical rock quality was poor.

In December 2014, excavation of the El Volcan Tunnel started with conventional drill & blast methods from the El Yeso portal. The excavation of the tunnel started in soil conditions (colluvium and sliding deposits) for a stretch of 30.55 m, to continue with 130.23 m of drill and blast excavation up to chainage 13+968.40 where the TBM would boring.

The Robbins TBM-1 started to bore on 15th June 2015, and during the first 15 days the TBM advanced 106.33 m along the tunnel. Rock mass presented good to fair quality with RMR values between 50 and 58 in the first meters of excavation with the TBM. Rock mass was composed of andesitic breccias with signs of alteration. The crown area was more fractured and it was observed that there were sub-horizontal joints that generated wedges and planar roofs.

During tunnel boring the most commonly anticipated support type was *rock support type I*, consisting of welded wire mesh and resin end-anchored rock bolts 2.4 m long and 22 mm in diameter, positioned to  $\pm 60^\circ$  and  $\pm 25^\circ$  at 2 m intervals. Less commonly used would be *rock support type II*, consisting of 7 cm of shotcrete, welded wire mesh and resin end-anchored rock bolts positioned to  $\pm 60^\circ$  and  $\pm 25^\circ$  at 2 m intervals. *Rock support type III* would consist of resin end-anchored rock bolts 2.4 to 3.9 m long and 22 mm in diameter, positioned to  $\pm 60^\circ$  and  $\pm 25^\circ$  as well as spot bolts at  $0^\circ$  every 1 m, along with welded wire mesh and 10 cm of plain shotcrete distributed through  $165^\circ$  at the crown. Figures 5 and 6 show the rock mass in a stretch with rock class II with sub-horizontal joints and RMR=51.

Figures 7 and 8 show the support increased to type III when rock mass became worse (RMR approx. 40), due to two sub-horizontal joint systems at the roof that generated significant over-break.



Figure 5. Planar roof and sub-horizontal joints



Figure 6. RMR=51



Figure 7. Sub-horizontal joints, RMR=42



Figure 8. 15 July 2015, support type III



Figure 9. TBM excavation, overbreak with RMR = 32



Figure 10. TBM excavation, overbreak with RMR = 32



Figure 11. Ch. 13+862.31 and Ch. 13+861.50, support type IV



Figure 12. Ch. 13+862.31 and Ch. 13+861.50, support type IV

Figures 9 and 10 show intense scaling after each TBM stroke when the rock mass continued getting worse, with more fractures detected and RMR ranging from 32 to 34. Three joints/faults systems were detected—two sub-horizontals and one vertical in the crown—that caused continuous over-break.

At a certain point, *support type IV* was required (Figures 11 and 12), which required yielding steel set installation due to the presence of a sub-horizontal fault/joint (dipping slightly upwards).

On 31st October 2015, the excavation works restarted with RMR ranging from 55 (type II) to 70 (type I), and with ground composed of andesitic breccia and sub-horizontal faults and joints that generated wedges and planar roofs.

On 8th December 2015 a 3 m long material detachment between the L1 and L2 area of the TBM was detected and loose material fell into the mesh, making it necessary to strengthen the support. The use of McNally elements as steel straps placed between rock bolts installed transversally and longitudinally around the affected area was instructed by the geologists, despite this support type not being part of the approved initial support design (see Figure 13).

Figure 14 shows the right wall and crown highly fractured with support type III installed.

McNally slats were installed in the top 150° with steel arches as well as 5 cm of plain shotcrete distributed in 150° at the crown as a result of the rock mass quality steadily worsening with highly fractured rock and a lot of material falling during excavation.

It is important to highlight that previous to this happening, scaling and use of support was what was used to control the over-break in the crown. However, this called for manual scaling and manual mucking of the unstable blocks and loose material, which ended up causing repeated damage to the TBM equipment and creating a potentially hazardous situation for the workers. The McNally System (specially designed for rock bursting conditions) combined with light arches solved both of these problems.

Exploration drillings were also carried out to detect the presence of water. A number of 30 m long consolidation grout injections up to 50 bar pressure were instructed by the owner. Even with these measures the rock conditions continued to be very poor with



Figure 13. 8th December 2015, McNally System as additional support due to material detachment



Figure 14. Advance 14th December 2015, Ch13+293

fractured rock, clay infillings and water inflows occurring due to the failure of the grouting works.

The sub-horizontal fault that had been initially detected continued, and faulted material got worse with crushed rock and significant clayey and weathered material. The presence of water washed out the clay, causing more over-break, first at the crown and over the machine, then later at the sides. These conditions required the installation of McNally systems and yielding steel arches in order to hold the loose rock again in place.

Due to the excess load (dead weight of loose rock) over the steel sets, the stretch was further reinforced with steel sets fixed with self-drilling bolts at the crown and resin end-anchored bolts at the sides and floor. During the drilling of the bolts it was detected that the fault presented a thickness of approximately 5.0 m, considering that rock appeared 1 m over the invert and 2 m from the crown.

In order to control the area, chemical grouting was required to fill the cavities produced by the combination of clay infillings and water inflow. This chemical grouting was carried out during the 14th to 24th of January 2016 (see Figures 15 and 16).

In a second step, a strong framework made up of mesh and shotcrete was prepared to consolidate and seal the area. Additionally, extra support was installed close to the steel set profiles as probe drilling was prescribed and this required partial cuts of some steel sets to properly execute the test.

### Conclusions for Alto Maipo

During the excavation of the El Volcan tunnel from the El Yeso portal, the presence of sub-horizontal joints and faults was continuously detected, which to a large extent affected and determined the excavation rates and the rock support requirements. These sub-horizontal structures along the excavation through the Abanico Formation had never been outlined in the Geological Baseline Report.

Standard ground support measures were applied to handle these sub-horizontal joints in the initial drill and blast excavation, but this became a serious problem for a small diameter (4,13 m) open-type TBM that in principle had been selected for good rock conditions. Under difficult ground conditions, the TBM operation demanded continuous manual scaling and manual mucking in order to remove loose material caused by wedges formed from these sub-horizontal joints in the tunnel crown.



Figure 15. Initial support including McNally slats and water inflow conditions



Figure 16. Initial support including McNally slats and water inflow conditions



The situation became even worse when these sub-horizontal joints turned into a sub-horizontal fault (shear fault) with an estimated thickness of 5 m, combined with high water inflow. This was managed with the application of all types of grouting injections.

The open-type main beam TBM provided by Robbins allowed quick access directly behind the cutterhead for the installation of rock support with rock bolts, steel mesh, ring beams, shotcrete and the McNally System, making this machine the most reliable and suitable choice for competent to slightly fractured rock. When the percentage of very poor rock mass quality is fairly small the machine is the superior method, as slow progress in bad ground can be compensated by the high excavation rates potentially reached under fair and good ground conditions. It may also be the preferable choice in heavily squeezing ground due to the short length of the machine front section (shielded area of about 5 m), since the ground may not deform fast enough to settle on the machine.

However, the TBM may not be the best choice when boring under extensive bad ground conditions with sub-horizontal joints and faults.

As a result of the lessons learned during the excavation under the above mentioned difficult ground conditions some improvements were implemented on the TBM:

- An extension of the side supports and the vertical front support to better face extreme squeezing ground conditions was carried out by means of the attachment of 3 × A572 GR50 steel plates (full penetration weld) to the existing side and vertical front support which extended the overall dimensions by 606 mm along each side and by 1264 mm for the vertical front support. The roof support length remained the same.
- A new probe drill setup was installed, aiming for a better lookout angle of 3 degrees to the roof. This included modification of the roof, side and vertical front supports by installing probe drill tubes and installation of a moveable drill ring that could travel 1500 mm and through two positions: a “working position” (only when probe drilling) at the aft end, and the “parking position” at the rear end, when no probe drill works were being executed. Roof drill travel was not affected, remaining with the original 2000 mm stroke.
- A mechanical system for removal of large blocks in the invert area was installed, including a handling sled with 0,5 m<sup>3</sup> capacity. The system was meant to be pulled under the bridge area by a winch system similar to the one used for pulling the disc cutters or steel ring.
- A newly designed dewatering system was installed to cope with 25 lps industrial water (dirty water) from the invert area and 100 lps infiltration water (clean water).
- New storage areas on the TBM backup system were installed for basic rock support materials such as steel sets, cement bags, rock bolts and others.
- A new, more user-friendly and versatile shotcrete robot setup was installed to reduce the shotcrete rebound.

As a result of these new features and modifications four (4) additional decks were added to the current backup system, including all associated changes and additions to conveying frames, piping, ventilation ducts and lines, cabling and hosing.

## LOS CONDORES HYDROELECTRIC POWER PLANT

“Clementina” is the name given by Endesa Chile to the 4.56 m (15.0 ft) diameter Double Shield TBM built specifically by The Robbins Company for the 150 MW hydroelectric power plant of Los Cóndores, which involves the excavation of a 12 km (7.5 mi) intake tunnel for a design flow rate of 25 m<sup>3</sup>/s.

The hydropower plant is located in the upper basin of the Maule River, 360 km south of Santiago, Chile, where water flow regulation will be made by means of the existing water reservoir of the Laguna El Maule. The project expects an average annual energy output of 642 GWh (48% load factor) and requires a total investment of US\$662 million. Operations are planned to start at the end of 2018.

The project key features are the water-intake facilities located at the reservoir Laguna del Maule at 2,500 m altitude, a 2x220 kV high voltage transmission line running for 87 km to connect the power plant to the substation facility, the 12 km long headrace tunnel, a 470 m-long vertical pressure shaft lined in concrete, and the turbine cavern.

The contractor responsible for the works, Ferrovial Agroman, met Robbins representatives in Solon, Ohio, USA in August 2015 to complete Factory Acceptance Testing of the TBM for the job. The Double Shield TBM was shipped to site in September 2015 to bore two sections of the tunnel lined with 4+1 concrete segments of 1,200 mm average length and OD 4,200 mm / ID 3,700 mm. The first tunnel section measures 6.0 km (3.7 mi) and the second 4.4 km (2.7 mi).

TBM site assembly started in mid-October 2015 onto a steel cradle provided by Ferrovial at “Plataforma Lo Aguirre,” a common laydown area for muck discharge and logistics for the two tunnels. Two months later, on January 2015, the TBM assembled onto the steel cradle was lifted and loaded onto a MAMMOET 27 m long x 3 m wide heavy lift 16-axle hydraulic modular motorized trailer specially designed for transport operations with heavy loads requiring a high bending moment (see Figure 17).

In a second step the entire assembly was transported through the 1,0 km long pre-excavated Drill & Blasting (D&B) access tunnel up to the launching chamber. Lashing material to prevent sliding and/or tipping of the load was used to secure the TBM and cradle onto Mammoet trailer as well as anti-slip material between all steel contact areas to promote friction (see Figure 18).

The TBM was launched in February 2016. Currently the TBM has bored more than 1.2 km of the access tunnel—the first drive (downstream) of the headrace tunnel.

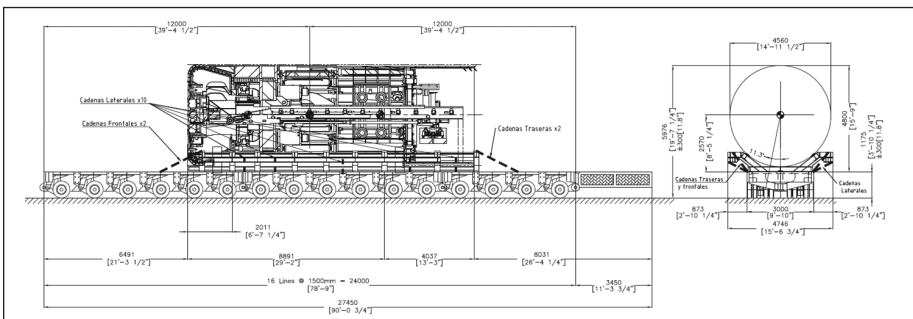


Figure 17. Mammoet heavy lift 16 axle hydraulic modular motorized trailer used to transport the TBM up to the tunnel launching chamber in Los Condores project

The tunnel is being bored at a maximum depth of 500 m below rock consisting of sandstone, tuff, and pyroclastic breccias. The rock was tested at strengths up to 100 MPa UCS, with at least two fault zones expected during tunneling.

### **Robbins Double Shield TBM by the Name of “Clementina”**

The Double Shield TBM “Clementina” provided by Robbins included many standard elements and several new features that were included to help the customer cope with whatever conditions may arise.

As standard, the TBM was built with a 2.65 m diameter main bearing for the 4.56 m outer diameter, as well as four variable frequency drive (VFD) electric motors that provide power to the cutterhead. Together with a maximum cutterhead thrust of over 22,000kN at 450 bar, the maximum cutterhead torque is over 1,800 kNm.

Among the specific features adopted for the TBM was the inclusion of gear reducers on the motors. By reprogramming the gearboxes on the VFM motors, extreme break-out torque could be increased.

The back-loading cutterhead is dressed with 30 × 17" Robbins wedge lock disc cutters and has a 19 mm to 12 mm wear capacity on the gauge cutters, depending on the cutter position. To be better prepared to cope with fractured and squeezing conditions, the cutterhead is also equipped with an overcutter facility. Once engaged, the overcutters can increase the bore dimension by 25 mm and 50 mm on the radius, corresponding to a tunnel increase of 50 mm or 100 mm on the diameter. The 50 mm overcutter setting on the radius is engaged in extreme squeezing ground and seriously reduces the risk of the shielded TBM becoming trapped. The overcutting facility can be adjusted through the crown and must be non-centric to the normal cut diameter to keep the invert of the extended cutterhead diameter on the same line. To achieve this, the cutterhead and the bearing unit is lifted onto a new axis.

Another special feature of “Clementina” is the system for probing and pre-excavation drilling should it be needed. Probing to >40 m ahead of the face is a systematic requirement.

The drill ports also allow for forepoling in an array over the crown and, in potentially squeezing conditions, lubrication of the shield can be injected through the same shield ports. Control and cleaning of muck is possible on the machines by closing off the muck chute in the excavation chamber with a horizontal guillotine door. The system will be used in the event that the cutterhead fills with material.

Drills are mounted on a ring beam providing for a permanent drill installation immediately behind the segment erector. From this forward location, the drill can install 16 drill holes on a 7 degree outlook angle through the drill ports around the forward shield (4 holes) and the gripper shield (15 holes) and through two horizontal holes in the cutterhead.



**Figure 18. TBM being moved into launching chamber**

Lastly, “Clementina” was specifically designed for disassembly and removal from a blind heading since there will be no possibility of breakthrough at end of each drive, neither at the upstream site of the new intake facilities nor at the downstream junction with the 470 m deep high-pressure shaft into the underground powerhouse. The TBM, therefore, will be dismantled within the finished tunnel and the components, including the sections of the cutterhead, retrieved back through the completed and segmentally lined tunnel. The machines has been designed and manufactured specifically to achieve this final operation with efficiency.

### **Challenges During Excavation**

Highly variable and rapidly changing ground conditions were encountered during the excavation of the first 1 km of the headrace tunnel downstream, including mixed-face conditions and unexpected and constant water inflow that presented great challenges and decreased the advance rates dramatically. These events, still ongoing at the time of paper writing, may trigger potential delays in the future if they are not addressed with a detailed understanding of the unfavorable conditions and the problems involved in TBM tunneling under mixed-face ground.

From the viewpoint of the rock-machine interaction, some mitigation measurements such as the selection of the correct TBM type, modifications and improvements on the TBM, conditioning of ground and finally the optimization of TBM operation are to be taken.

### ***Muck Chute Failure Under Highly Variable and Rapidly Changing Ground Conditions***

Mixed ground conditions with very hard andesite (up to 150–200 MPa) on one side of the tunnel face and a very fine hydrothermal sand deposit from rhyolite on the other side were encountered. Combine this with a larger than normal rotatory unit to accommodate the many cutterhead ports, and the reduced capacity muck chute is what contributed to the failure and forced the TBM to stop for three weeks until a new muck chute was provided and installed.

This issue typically occurs in blocky ground when a boulder becomes caught between the muck chute and the rotating cutterhead. When the muck chute becomes blocked, the rock and material will usually overspill the chute. However a blockage can also occur in sticky clays or loose material (sand), especially when the muck chute spoil window is not big and the impact pad is not steep enough for fine material.

The real issue to overcome is to prevent boulders from getting caught between the cutterhead and muck chute. The operator must be aware of the ground conditions and the chance of boulders entering the cutterhead, and capable of recognizing the sign of a boulder getting caught (basically a large jolt of the machine as the boulder gets caught between the muck chute and the cutterhead). The operator must then stop the cutterhead as soon as possible to prevent it from being sheared off (see Figure 19).

As it is more a matter of keeping the cutterhead clean and ensuring the correct hardware is in place, Robbins and Ferrovial decided to revise the cutterhead inspection protocol and have the personnel in charge of the tasks ensure the cutterhead is being cleaned thoroughly, including checking the bucket lips and grill bars more often.

If blocky ground is not the root cause for the chute failure, then increasing the discharge capacity of the muck chute may be the right decision to make. A tradeoff between the rotary union capacity to fit as many injection ports as practically possible and a chute

with a steeper front loading plate to better handle the actual ground conditions (soft ground) was made, even when that entailed downsizing the rotary union and associated manifold and plumbing. This therefore affected the capacity to inject foam, water and other additives. A revision of the general assembly with a new belt length and modified take up frame was also required.

### **High Water Inflow Rates**

Another no less important challenge has been the steady increase in water inflow up to a maximum of 3,500 l/min. The presence of water exacerbated the issue of face stability by washing away the small particles of weathered rhyolite that allowed progressively large sections of the face to become unstable and added fluidity to in-situ ground and excavated muck. This fluidized muck made it more difficult to control the flow into the head, the telescopic shield and into the rear section in the ring building area.

Small particles of sand dragged by the pressurized water inflow remained accumulated underneath the main thrust cylinders and caused continuous damage to them during the re-gripping operations. Water inflow also made it harder for the customer to keep the annulus grout from washing out.

Depending on conditions, i.e., water quantities, pressures and flow rates, some methods have been tried:

- Add anti-dilution additives to the grout
- Inject sodium silicate into the grout at the injection nozzle to achieve a very rapid set without negative effects of too much water in the annulus. Dosages to be tried and evaluated outside of the tunnel first.
- Selectively drain the annulus (de-pressurize); i.e., locally pull the water out and replace with grout
- Selectively drain the nearby rock mass
- Do more pre-excitation grouting in front of or around the TBM

In all cases, it is necessary to keep the annular grouting program around the segmental liner “tight” to the tail shield since lots of water is often released from the rock mass as soon as the cutterhead passes. These modifications are still in progress and a more detailed report of the most successful options will be provided during the conference presentation.

## **FINAL CONCLUSIONS**

Whether an open type, Main Beam TBM or a shielded hard rock TBM, the Andes is a mountain range that presents challenges. While both projects utilize different methodologies—McNally slats at Alto Maipo contain ground in combination with other forms of support, while concrete segments will line the entire Los Condores Tunnel—both are successful methods. Shielded TBMs can be outfitted with a number of additions including multi-speed gearboxes and shield lubrication to avoid the problem of



**Figure 19. Blocky material (andesite with fine sand from weathered rhyolite) inside the cutterhead**

machine shields becoming stuck in fault zones. As such, both shielded and open-type machines are capable of performing well in fractured rock. In both cases common methods, including continuous probe drilling and grouting, can inform operators of conditions ahead of the TBM in order to make adjustments accordingly, grout off water, etc. And in both cases well-trained operators and a team with agreed-upon protocols for bad ground conditions is key to project success. As both machines navigate the challenging Andes Mountain range we will continue to analyze and further refine our opinion of the two excavation strategies.