**TBM Partial Excavation, Challenges and Solutions**

*Case study and lessons learned from the Airport Link TBM (Brisbane/Australia)*

By: Keivan Rafie MEng PEng (E.Aust.)

**Abstract**

The Airport Link is the largest construction project in Australia, located in the northern suburbs of Brisbane/Queensland. Two Earth Pressure Balance TBMs that are each approximately 165 m long with a diameter of 12.45 m constructed more than 2 km of this project. These tunnels connect the Brisbane central business district and the Clem Jones Tunnel to the East-West Arterial Road, which leads to the Brisbane Airport. Tunnel geology varies from Alluvium to Siltstone to Sandstone and Tuff, and the construction cost of the project was reported to be over AUS$ 4.8 billion.

Along the alignment, both TBMs passed through caverns that had been excavated by road headers according to the NATM style. These huge caverns were designed to connect the entry and exit ramps halfway through the tunnels. After considering several options for the TBMs to pass the cavern after break through, the contractor decided to choose a partial excavation and use segmental lining in the invert to push the TBMs forward before reaching the other end of the cavern for the relaunch.

Near the end of March 2011, less than 10 m of the southbound cavern was left for excavation, and the TBM was entrapped in the smaller pre-excavated profile, which was designed for relaunch. This paper discusses the challenges and operations involved in the TBM partial excavation, the reasons that led to the TBM entrapment and the method used to break the TBM free and restart its operation for the 2nd launch.

**Résumé**

Une voie d’accès à l’aéroport, The Airport Link, est en construction en banlieue nord des villes de Brisbane/Queensland ; il s’agit du plus important projet de construction actuellement en cours en Australie. Deux tunneliers à pression statique d’environ 165 m de longueur et d’un diamètre de 12,45 m ont creusé plus de 2 km de galeries dans le cadre de ce projet. Ces galeries relient le centre d’affaires de Brisbane et le tunnel Clem Jones à l’artère Est-Ouest menant à l’aéroport de Brisbane. La géologie du tunnel est composée de dépôts alluvionnaires, d’argile, de grès et de tuf, et les coûts de construction s’élèveraient à plus de 4,8 milliards en dollars australiens.

Pour le forage des galeries, les deux tunneliers ont traversé des cavernes excavées par des machines de traçage dans le style de la NATM. Ces immenses cavernes ont été conçues pour relier les rampes d’accès et de sortie à la mi-chemin des tunnels. Après avoir considéré plusieurs options concernant l’utilisation
des tunneliers pour traverser la caverne, l'entrepreneur a opté pour une excavation partielle avec recours à une doublure segmentaire du radier pour faire progresser les tunneliers vers l’autre bout de la caverne avant de reprendre le forage.

Vers la fin de mars 2011, avec moins de 10 m de caverne en direction du sud à excaver, le tunnelier fut coincé dans le profil pré-excavé de dimension plus petite qui avait été conçu pour un relancement. Cet article examine les défis et les opérations d’excavation partielle, les raisons qui ont mené au coincement du tunnelier et les moyens utilisés pour libérer la machine et reprendre les opérations.

Introduction

On 19 May 2008, the state government announced BrisConnections as the preferred bidder for the Airport Link and Airport Roundabout Upgrade projects. BrisConnections contracted a joint venture between Thiess Pty Ltd and John Holland Group for the design and construction of the Airport Link. The Airport Link project involved 15 km of tunneling, including the road (5.7 km of twin tunnels), bus-way tunnels and connecting ramps, as well as 25 bridges, resulting in over 7 km of new road.

Two Herrenknecht double shield TBMs, each with a diameter of 12,340 mm, had tunneled the Clem Jones Tunnel under the Brisbane River by May 2009. The Airport Link will be an extension of this tunnel project. The S-512 (Sandy) and S-514 (Rocksy) earth pressure balance shields, with diameters of 12.45 meters each, are larger than the Clem Jones twins, making them the largest machines that have been used for tunneling in Australia.

Each TBM bore a road tunnel that is approximately 2.5 km long. The two machines began tunneling in July and August 2010. After 12 months, Rocksy reached its target on July 4, 2011, while Sandy achieved the same target two days later (July 6).

Tunnel Alignment & Geology

The tunnels are connected to the surface via cut-and-cover structures at Bowen Hills (Southern Connection), Kedron (Midway) and Toombul (Eastern Connection). Each TBM drive will begin at Toombul and proceed towards Lutwyche in the southwest direction. The mined caverns at Kedron effectively split each of the TBM drives into two sub-drives: a longer drive from Toombul to Kedron and a shorter drive from Kedron to Lutwyche.
The ground conditions for TBM drives consist of a complex geological setting comprised of alluvium, sedimentary materials, carbonaceous siltstone and conglomerate underlain by Brisbane Tuff. The groundwater regime along the Airport Link project alignment comprises two aquifer types; the ‘lower aquifer’ includes a fractured rock aquifer system within the Neranleigh Fernvale Beds, Brisbane Tuff and Tingalpa and Aspley Formations, and the ‘upper aquifer’ includes the quaternary alluvial systems within the Enoggera Creek and Kedron Brook valleys.
**TBM Specification**

The contractor purchased two EPB shield TBMs from Herrenknecht, Germany. Each TBM was designed for 2400 m of tunnel with a minimum curve radius of 750 m and a working pressure of 4 bar. The cutter head had a bore diameter of 12,480 mm and weighed 213 tons. The cutter head tools consisted of 70x-17” disc cutters, 180 cutting knives (scrapers) and 16 buckets. The TBMs had 14-x-250-kW motors that provided a rotational speed of 3.65 rpm to the cutterhead with a nominal torque of 20.4 MNm. The TBMs had 38 main thrust cylinders (19 Rams) with 2800 mm of stroke and 90,000 kN of thrust force.
Passing through the Kedron Caverns

For the TBMs to pass the Kedron caverns and prepare for a second launch at the opposite end, a few options were considered. The first concept was to slide the TBMs though the caverns on a special rail and cradle. Another option was to disassemble and move the TBM pieces to the new location. The last option involved partial excavation, in which TBMs would excavate the invert of the cavern and use precast segments that were built in the area to propel themselves forward.

After weeks of planning, risk assessment and comparison between all options, the contractor selected the ‘Partial Excavation’ option. One of the major benefits of this method was that it involves laying down
the road decks, similar to the full-face excavation, and it uses the excavated area for the extension of the utility tunnel along the cavern.

Performing Partial Excavation

Partial excavation (‘making the TBM crawl’) revealed many challenges. Some of these challenges were considered in advance, and others were first encountered during the operation. Although the TBM crew and engineering team were well experienced in TBM tunneling, for most, ‘partial excavation’ was a new concept that required several alterations from the common TBM operation rules. Certain aspects of this challenge are discussed below.

Steering the TBM and Ring Installation

To propel and steer the TBMs, precast segments were installed at the curved excavated profile of the cavern. The TBMs could then advance using the selected bottom propulsion cylinders. Steering the TBM to left and right was performed only with the differential forces of the seven rams located in that area. Because normal TBM operation involves working with rams in groups, new operating methods to control each ram individually had to be developed. For this purpose, electrical and mechanical technicians worked together to make the required modifications to the TBM computer and propulsion systems.
Additionally, selection of the ring positions had to be modified. Because rings were universal, the TBM ring selection required a sequence of rings that neutralizes the effect of the tapered segments and is compatible with the straight alignment of the cavern. To overcome this challenge and ensure that all of the manufactured segments in each ring were used, the contractor designed a sequence of ‘half-ring’ positions, which were repeated every four rings with theoretical directions at 12, 3, 6 and 9 o’clock. This arrangement neutralized the ring taper, aligned the TBM on a straight line and minimized the number of unused segments.

**TBM Sink and Roll**

The partial excavation was found to potentially cause the TBM to sink into the ground. Calculations showed that the TBM needs a support or minimum invert thickness to stop the forces on its center of gravity from causing it to sink into the ground. Additionally, a muck extraction strategy in front of the
TBM required the one-way rotation of the cutter head (discussed below). Without a full face, the TBM is highly vulnerable to roll in the opposite direction of the cutter head rotation.

Analysis of forces on the TBM’s center of gravity

After extensive discussion and investigation, two elements were designed to address these risks. The first element is a concrete curb, which is poured on both sides of the TBM along the cavern. The second element is a set of special anti-roll/sink brackets that are welded to the TBM shield, which can slide on the curb, preventing the TBM from sinking into the ground or rolling while the invert is being excavated.
Concrete curb for sliding the anti-roll brackets

Flying Gantries and Final Tunnel Profile

Another concern for TBM movement through the cavern is the supporting flying gantries, which, by default, move on wheels that are on rails. These rails were installed with brackets on segments located just below the tunnel’s spring line. Loads from the weight of the TBM flying gantries were transferred to the surrounding ground through the segmental lining. With the partial excavation arrangement, the TBM half-rings were designed to be extended above the invert level to accommodate the brackets on every second ring on left and right sides of the tunnel. However, without ground support behind these extended segments, loads from the TBM can damage/displace the segment, create major worker safety risks and compromise the TBM gantries’ integrity.

Extended segments and flying gantry rails
To overcome this problem, special support struts were designed and installed around the extending segments to hold the brackets and TBM flying gantries. Because the extending segments needed to be trimmed for the final tunnel profile and did not require support struts after the TBM flying gantries had passed, two final operations were performed. First, the support struts were disassembled and leapfrogged ahead to where the flying gantries approach the newly installed half-ring, and then the half-segments were cut to match the profile of the cavern. A special structure was designed and attached to the TBM to facilitate this operation. Saw cutting of the segments was performed by mounting a horizontal rail on the previous and following segments and using a circular saw to cut the segment with high precision.
Muck Extraction and the Conveyor Belt

Muck extraction in the partial excavation was performed from both sides of the cutter head. Because some of the excavated material falls around and in front of the TBM, medium-sized excavators were used in front of the TBM to load the muck onto trucks for extraction from the tunnel. Part of the material that was falling into the chamber was extracted with a screw conveyor into the conveyor belt and transferred to the shaft similar to normal TBM operation.

Extracting the material in front of the TBM revealed several challenges. The most important challenge involved collecting the muck from the left and right sides of the TBM. On the side of the TBM that was closer to the cavern walls, the excavators had difficulty reaching the material that was stuck between the cavern wall and TBM. On the opposite side, the excavated material was dispersed such that the excavator operator had difficulty efficiently filling buckets.
As a result, the contractor proposed two ideas to more quickly progress the operation. The first idea involved rotating the cutter head in a direction such that the muck accumulated on the side with easier access. This required anti-roll brackets, which were discussed in the previous section. The other modification involved welding ‘Hungry Boards’ to both sides of the TBM, which pile the material for the excavator operator to more efficiently fill buckets.

Excavating the material in the chamber and transferring it from the TBM through the belt conveyor revealed another challenge to the team. The cavern invert preparation and certain other operations on the connecting ramps needed to be performed as soon as the last TBM gantry had passed the area, but the conveyor belt, which was extended behind the TBM, was restricting the access of other crews. Therefore, the contractor investigated certain options and decided to lift the belt within the cavern to support it from the roof. This system was called the ‘flying conveyor’. This arrangement provided access to all traffic in the area. The utility lines were also relocated to the underside of the road deck, which was available due to the TBM partial excavation method.
**Entrapped TBM and Solution to Break Free**

At approximately the end of March 2011, with less than 10 m of the southbound cavern left to be excavated, Southbound TBM (Sandy) was entrapped in the smaller pre-excavated profile. This section was excavated by road-header to accommodate the design for the relaunch frame and other elements.

The relaunch procedure, in brief, consisted of:

- Disassembling anti-rolls and cutting off Hungry Boards
- Welding new hard-facing blocks and welding new Tailskin brushes
- Excavating the invert through the stub tunnel
- Installing thrust ring for relaunch
- Building full rings until the cutter head contacts the face
- Resuming excavation for the second drive
The chain of events that led to the TBM jam occurred during rings 718 to 720. Around this area, the TBM entered the smaller stub tunnel profile and was close to its final position for relaunch. The survey revealed that the TBM was slightly higher than the designed alignment (DTA), and the TBM operator was asked to center the TBM before the cutter head stopped for the relaunch preparation. Within a few rings of the final position, the TBM operator used a sharp overcut to return the TBM to the center. It should be noted that because the anti-roll/sink brackets were installed on both sides, the TBM could only deviate from the DTA by moving upwards.
The overcut was set to 6 o’clock many times before and during the partial excavation to allow the TBM to land with its ‘shoes’ on the concrete curb. This time, with a few rings left, the same practice was performed by the operator, except that the TBM’s surrounding conditions were changed and that the front shield of the TBM had entered the stub tunnel.

At this stage, the top section of the TBM shield had a small clearance with the roof of the stub tunnel. However, the TBM still had no back support for the top or middle rams and was only pushing with the invert rams. After the operator changed the setting of the TBM to perform a high overcut at the bottom, the TBM was forced to move through a sharp vertical curve in the span of a 2- to 3-m advance. This movement caused the top of the shield to become trapped on the roof of the stub tunnel. This friction, which stopped the TBM, is generally not large enough to stop the TBM if all of the thrust cylinders are operational. However, with no force available except for the rams in the invert, TBM could not overcome the frictional forces in the crown. More thrust on the lower thrust cylinders only exacerbated the situation and made the TBM reach a complete halt. The yellow row around ring 719 in the table below shows the point at which the high thrust was first noted. The last row is the point at which the TBM stopped moving due to the excessively high thrust.

<table>
<thead>
<tr>
<th>Ring no.</th>
<th>Ram Stroke</th>
<th>Displacement Position Top</th>
<th>Difference Over 12.45 m</th>
<th>Overcut</th>
<th>Forward shield Chainage</th>
<th>Gauge cutter Chainage</th>
</tr>
</thead>
<tbody>
<tr>
<td>718</td>
<td>584</td>
<td>110</td>
<td>0</td>
<td>0</td>
<td>1440.082</td>
<td>1440.712</td>
</tr>
<tr>
<td>718</td>
<td>1891</td>
<td>124</td>
<td>62</td>
<td>10</td>
<td>1441.389</td>
<td>1442.022</td>
</tr>
<tr>
<td>718</td>
<td>2549</td>
<td>130</td>
<td>90</td>
<td>15</td>
<td>1442.047</td>
<td>1442.681</td>
</tr>
<tr>
<td>719</td>
<td>574</td>
<td>130</td>
<td>90</td>
<td>15</td>
<td>1442.047</td>
<td>1442.681</td>
</tr>
<tr>
<td>719</td>
<td>633</td>
<td>151</td>
<td>176</td>
<td>30</td>
<td>1442.106</td>
<td><strong>1442.745</strong></td>
</tr>
<tr>
<td><strong>719</strong></td>
<td>1667</td>
<td>151</td>
<td>176</td>
<td>30</td>
<td>1443.14</td>
<td>1443.779</td>
</tr>
<tr>
<td>719</td>
<td>1710</td>
<td>137</td>
<td>117</td>
<td>20</td>
<td>1443.183</td>
<td>1443.819</td>
</tr>
<tr>
<td>719</td>
<td>2453</td>
<td>156</td>
<td>176</td>
<td>30</td>
<td>1443.926</td>
<td>1444.5705</td>
</tr>
<tr>
<td>719</td>
<td>2706</td>
<td>156</td>
<td>176</td>
<td>30</td>
<td>1444.179</td>
<td>1444.8235</td>
</tr>
<tr>
<td>720</td>
<td>720</td>
<td>156</td>
<td>176</td>
<td>30</td>
<td>1444.179</td>
<td>1444.8235</td>
</tr>
<tr>
<td>720</td>
<td>1414</td>
<td>144</td>
<td>87</td>
<td>15</td>
<td>1444.873</td>
<td>1445.5215</td>
</tr>
<tr>
<td><strong>720</strong></td>
<td>1638</td>
<td>144</td>
<td>87</td>
<td>15</td>
<td>1445.097</td>
<td><strong>1445.7455</strong></td>
</tr>
</tbody>
</table>

TBM parameters during the last three rings before it stopped

Using the available rams in the bottom section of the TBM, the operators were instructed to tilt the TBM by separating the rams into two groups (left and right). The operators tried to apply the maximum force on the left side and then the right side. This method allowed the TBM to move a few millimeters around invert with no forward movement in the crown.
The next method to release the TBM involved pumping bentonite around the shield through the ports to lubricate the area surrounding the TBM while applying the previous strategy of pushing with the left and right side rams, consecutively. This method was also unsuccessful.

When it was clear that the TBM could not break free from the control cabin, the TBM crew entered the excavation chamber and attempted to break the rock surrounding the crown at the expected highest point of friction with the surrounding rock. The TBM crew broke approximately 1 m of rock in that area with mechanical tools and tried the former methods again with no success. It was suggested that because only the bottom rams were used for each attempt, every push that did not break the TBM free made the condition worse by pushing the TBM into the crown.

Water jet blasting was also considered, and a jet lance with a modified nozzle was welded to the inside of the cutter head with the nozzle pointing towards the perimeter of the TBM shield. With this arrangement, jet blasting could be performed by rotating the cutterhead along the perimeter of the shield; however, this method was also not successful in releasing the TBM.
Breaking rock at the crown with drills and a ‘water jet’

When all of the available methods failed to free the TBM, the contractor was convinced that without force coming from the rams at the top, the TBM could not break free regardless of the modifications or work that the TBM crew performed around the shield. However, using the rams at the top without segmental lining is challenging.

After assessing several options, it was decided to design a ‘thrust block’ and ‘extension struts’ system to use the few rams at the top. This block of concrete was attached to the roof of cavern with 12 steel bolts that were inserted deep into the rock at an angle such that when the TBM applies force to the thrust block, the bolts will react in tension and transfer the loads into the ground. The thrust block was reinforced with rebar and poured with concrete after installation of the bolts. Later, when the concrete reached the required strength, all of the bolts were pre-tensioned and tested for a minimum of 5 minutes (100 KN each) to verify their installation quality and anchorage in the rock.
Next, extension struts were attached and welded to the TBM shield to fill the space between the thrust block and thrust cylinder pads. In this manner, the forces were shifted to the thrust block and then the rock through the tension in the bolts.

After the installation was complete, the TBM cutter-head was retracted by approximately 100 mm, and the overcut was set to zero. The solenoids on the top rams (1 and 19) were reinstated, and the surveyors were asked to check the thrust block for movement. Rams 1 and 19 were slowly extended, and the minimum pressure was applied to contact the extension struts. The TBM was able to successfully propel itself forward for 100 mm without the cutter head rotation to break free, and the normal excavation continued for the next few meters until the TBM reached the final position for the relaunch.

**Conclusion**

Passage through Kedron caverns by partial excavation was successfully completed. Both TBMs bored the second drive after relaunch and finished the 2.5 km long twin tube tunnels. Rocksy reached its target on July 4, 2011, and Sandy achieved the same target two days later (July 6). The Airport Link project is scheduled for completion by mid-2012.

TBM tunneling has been increasingly applied to construct tunnels in urban areas. Urban tunnels and underground spaces are increasingly complicated, and more interfaces are required between TBM and other methods of tunneling such as road header and drill and blast. These interfaces bring many challenges that may be addressed with proper engineering approaches and prior consideration at the design phase of the projects. It is necessary to examine additional challenges and experiences within the tunneling industry using case studies such as the present one to increase the efficiency of tunneling.