19th Australasian Tunnelling Conference – Acosta-Martínez, Stewart and Hudson-Smith (Eds.)
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TBM excavation in poor squeezing ground condition. The LPFZ crossing in Snowy 2.0

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ABSTRACT: The "Long Plain Fault zone" (LPFZ) is a challenging stretch of the Headrace Tunnel with highly squeezing and fractured ground, faults up to 50% frequency, and fault zones thicknesses up to 40m. A recent geological investigation revealed the original plan to use TBM#1 generates unacceptable risks of prolonged shields jamming. It was therefore decided to adopt a different and innovative technology and methodology that foresees the use of new and different type of machine, TBM#4, a trial-mode Open/EPB/Variable density TBM capable of applying up to 8 bar active support pressure and to cope with the different criticalities expected along the drive. Additionally, the design and implementation of a complex drainage system to reduce the pore water pressure in weathered shear zones, thereby increasing effective soil stress and stabilizing the surrounding ground.

1 INTRODUCTION

This paper presents the innovative solution developed by Future Generation Joint Venture (FGJV, led by Webuild) for excavating a tunnel section with extremely poor, highly convergent ground conditions (the LPFZ) using a Tunnel Boring Machine (TBM). In Australia, where experience with such geology is limited, conventional excavation would have posed greater risks and complexity. The TBM approach supports project schedule requirements. The solution was developed collaboratively by FGJV, the design joint venture (DJV) including Lombardi Group, TBM supplier Herrenknecht (HKN), technical teams from Webuild and Snowy Hydro Ltd. (SHL), and independent consultants such as ARX. Excavation of the LPFZ is set to begin in June 2026.

2 SNOWY 2.0 PROJECT

Snowy 2.0 is one of the world's largest pumped hydro schemes, highlighting the Snowy Scheme's critical role in the National Electricity Market (NEM). It will add 2,200MW of generation capacity and provide around 350,000MW/h of energy storage. The project includes intake and outlet structures at Tantangara and Talbingo Reservoirs in Kosciuszko National Park, 27km of concrete-lined tunnels between the reservoirs, 20km of supporting tunnels, and an underground power station nearly 1km deep. FGJV—formed by Webuild, Clough, and Lane—was established to deliver integrated engineering, procurement, and construction management services, drawing on extensive global infrastructure expertise.

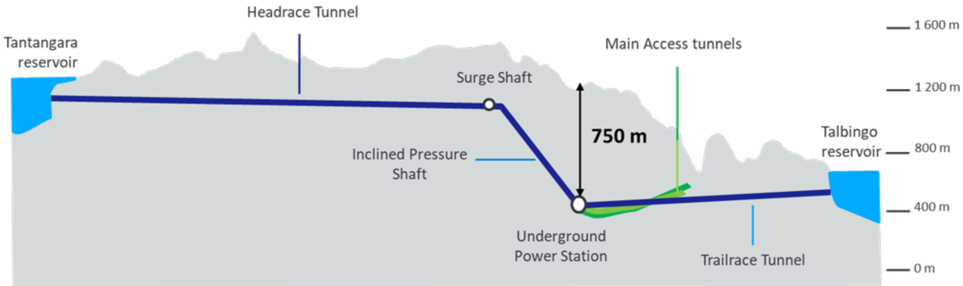

Figure 1. Snowy 2.0 Project Alignment

3 GEOLOGICAL AND GEOMECHANICAL CONTEXT

From the geotechnical point of view one of the most challenging sections of the entire project is the excavation of the Headrace Tunnel, running from the Tantangara Reservoir to the Upstream surge shaft. This is a 17,3km long “wet tunnel” with an inner diameter of 9,9mt. As per the tender scheme it was expected to be excavated entirely using two TBMs. The geotechnical baseline report was indicating a very variable ground across the entire length of the drive, with soft and hard rocks, several possible faults, risk of asbestos fibers, and a long stretch of poor material of approx.1650m known as the Long Plain Fault Zone (LPFZ), which required a specific further investigation campaign, after the project start date. Two additional directional boreholes drilled from the surface and parallel to the entire LPFZ were executed between the end of 2023 and early 2024 (BH5401 and BH5402/BH5402W1). They showed a more extensive section of very poor rock mass properties compared to the previous profile.

The LPFZ is falling into the Ravine Bed East formation (RBE), which comprises interlaminated siltstone and sandstone with occasional thicker beds of each of these lithologies. The rock mass is highly fractured, typically spaced at 60 to 200 mm, and crushed zones and sheared seams are often observed. This unit has a steeply dipping foliation with dips of 45-60° towards the E-SE, with a slaty cleavage appearance and common quartz veining and less common intrusive dykes described as volcanics and ignimbrites/tuffs of rhyodacitic, basaltic and andesitic composition. Rather than a well-defined fault, the LPFZ is a wider zone in which sections of highly disturbed rock mass (faults and fractured rock mass) alternate with section of relatively undisturbed rock mass. After the last geotechnical investigations, over a total LPFZ length of approx. 1650mt, it has been identified a stretch of approx. 815mt with a higher frequency of faults between 30% and 50% and thickness up to 40m. The most relevant update of the last campaign is represented by the description of the LPFZ structure, by defining three different typical rock mass conditions classified by colours on the basis of the Fault frequency:

1- Green zones, where fault frequency is less than 10% and the FZ thickness is generally less than 1m. The rock mass presents relatively good conditions. These conditions are expected in the external portions of the LPFZ;

2- Yellow zones where fault frequency is less than 30% and the FZ thickness is less than 5m. These rock-mass conditions, intermediate between green and orange zones, represent the transition zone from the external part (Green stretch) towards the central part of the LPFZ where the shear is more pervasive;

3- Orange zones, where the fault frequency is up to 50% and the FZ thickness up to 30-40m. It is expected in the central part of the LPFZ and it represents the worst rockmass conditions along the HRT. The high heterogeneity of the ground is here defined by the alternation of good quality rock layers and layers of fault with gouge and/or fault breccia. The presence of high intensity faults in the Orange zone, often containing gouge in variable proportions, required an in-depth analysis of the factors predisposing a risk of TBM jamming. The thicknesses of the prevailing gouge represent the most severe conditions identified for jamming risk, which have been assessed also considering the scale of the tunnel, and the contribution of the adjacent materials, represented by breccias and fractured rock masses, whose deformability generates a lower risk of jamming.

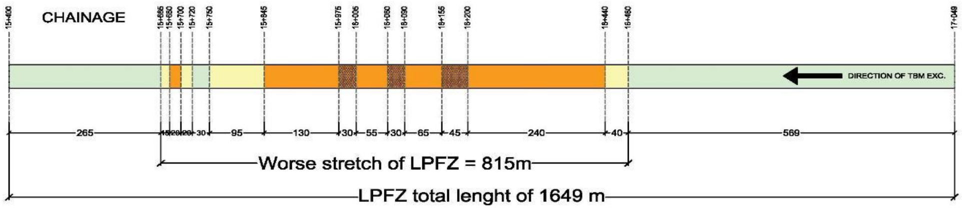

Figure 2. LPFZ different rockmass condition and distribution.

A critical factor for the evaluation of the excavation method was also the permeability value (k). The permeability observed in packers and DST tests. The Fault Zone was defined with a low permeability of $4*10^{-8}$ m/s to $1.2*10^{-9}$ m/s, while for the *prevalent gouge*, given that the fine-grained nature of the material, a single permeability of $1.2*10^{-9}$ m/s was selected. Unfortunately, with the available information it was not possible to determine the exact distribution of the permeability across the worst stretch of the LPFZ. What is known is that higher range permeability in the orange zones represent the more complex scenario to be considered, with a high convergency risk of more than 5%.

4 RISK OF ENTRAPMENT OF TBM#1 ALREADY MOBILIZED IN THE PROJECT

The TBM#1 jamming risk was evaluated by Lombardi Group by means of an axisymmetric model (3D cylinder) that simulates the TBM advance along the central axis with fully coupled analyses (mechanical and hydrogeological equilibrium are managed simultaneously). Starting from a predefined pressure on the excavation boundary (i.e. the maximum pressure that can be assumed according to TBM#1 data), a calculation of the ground displacement along the tunnel axis and a comparison between this displacement profile with the TBM#1 geometry has been assessed. A sensitivity study with several combinations of parameters has been performed with the Software FLAC developed by Itasca Consulting Group Inc., USA. Below are reported the most relevant two cases that essentially shows the great influence of the ground permeability on the TBM#1 jamming risk.

							TBM jamming (excessive displacement for the shields)					Face stability		
Case	φ	c	k	P_F	P_{10m}	P_{rad}	TBM#1 - Standstill time					TBM#1 standstill time		
	[°]	[kPa]	[m/s]	[kPa]	[kPa]	[kPa]	0 h	12 h	2 days	4 days		12 h	2 days	4 days
14	30	10	1.20E-09	200	1000	2000	✓	✓	✓	~		✓	✓	~
16	35	300	1.20E-08	200	1000	2500	✗	✗	✗	✗		✓	~	✗

✗ TBM jamming expected	✗ Extrusion > 30 cm
~ Possible risk of TBM jamming	~ Extrusion = 15-30 cm
✓ Low risk of TBM jamming	✓ Extrusion < 15 cm

Figure 3. TBM jamming risk analysis for 2 load cases, considering radial convergencies and face extrusion.

Case 14 shows the results of a simulation with poor geotechnical parameters (friction angle of 30° and cohesion c of 10 kPa) and a ground permeability of 1.2E-9 m/s. Under such conditions, the TBM#1 could withstand a standstill of up to 2 days since the convergence profile is compatible with its geometry. However, it must be noted that the required TBM-thrust force during excavation is about 120 MN, which corresponds to the total thrust at max. operating pressure, while during standstill the required TBM-thrust force increases to approx. 200 MN, slightly above the total exceptional thrust of TBM#1. Therefore, the analysis is really at the limit.

Case 16 shows the results of a simulation with better geotechnical parameters than case 14 (friction angle of 35° and cohesion c of 300 kPa). However, since a higher ground permeability has been considered (k = 1.2E-8 m/s), the results show that under such conditions the jamming of TBM#1 is expected since the convergence profile is not compatible with its geometry.

The result of the analysis indicated high jamming risk of the TBM#1 along the poorest geological stretch of the LPZF (the so called "orange zone"). The main parameter governing this risk are the geometry of the TBM#1 and the assumed ground properties, especially the permeability (higher permeability leads to a higher jamming risk).

	Allowable days of TBM#1 stoppage before jamming	
Permeability variance in the worse stretch of the LPFZ (approx. 520 m)	Convergence on the shield	Face extrusion
Lower – $k = 10^{-9}$ m/s	4 days	4 days
Medium – $k = 1.2 \times 10^{-8}$ m/s	0 days	2 days
High – $k = 4 \times 10^{-8}$ m/s	0 days	0 days

With both medium and high permeability, convergencies on shield and face extrusions are too high, even if the TBM#1 is never stopping across those zones, which is not possible. In all those cases TBM#1 will be blocked (Un-reasonable risk of prolonged jamming).

Figure 4. Influence of permeability (k) in TBM#1 jamming risk and allowable standstill time.

5 TBM#4 SPECIAL DESIGN

TBM#4, employed in the Snowy project, was specifically designed to address the challenges posed by the LPFZ, mainly the high convergences of the ground and its pressure on the TBM shield. As such, it integrates a range of technical solutions that make it unique in its class. The fundamental geotechnical risks when planning tunnel projects, which are relatively high within the LPFZ, especially in the current case for snowy 2.0, can be largely compensated for by choosing the most suitable TBM type, in accordance with DJV recommendations. By considering the worse possible ground behavior, Lombardi Group indicates the following main characteristics:

a) Total shield length reduced to 11,2 m, with consequent reduction of the ring length;
b) Shield conicity of 85mm, with additional overcutting capacity up to 130 mm on radius
c) Tail shield able to resist up to 20 bar of ground pressure
d) Exceptional total thrust of 250.000 KN, nominal of 157.000 KN
e) Active operative face support pressure of 6bar, nominal of 8bar.

TBM shall provide the possibility of applying active support pressure to pass through the LPFZ, as the tunnel face is expected to be unstable in some sections and the strong weathering/shearing of the rock means that a classic hard-rock cutterhead reaches its limits when it comes to soil excavation or mucking. The muck channels or the openings for the buckets of the cutterhead would quickly become blocked and the feasibility of the TBM would even be called into question. Therefore, the two TBM types EPB or Slurry were basically the only recommended for tunnelling through the LPFZ, or a combination of both. A technical comparison was made between Slurry and EPB TBM, particularly focusing on the capability to operate in pressurized mode with large conicities and extreme overcutting.

A Slurry TBM can operate at higher pressures and uses a low-density slurry to pressurize the face and to transport the muck along the tunnel through a pipeline. But in this specific case due to the large gap between the excavation profile and the shield and the potential high risk of over excavation at the crown of the tunnel due to the poor ground conditions, it would be difficult if not impossible to keep the low-density slurry confined under pressure at the face; it will rather flow away in an uncontrolled manner through the large gap between the shield and the excavation profile and through the overbreak's in the tunnel crown.

On the contrary an EPB TBM uses a very dense paste to pressurize the face. This paste, formed by the excavated material mixed with conditioning agents, being very dense will fill the gap between the excavation and the shield without flowing away. At the same time the dense EPB paste that fills the gap between the excavation and the shield and provides good confinement and support to the TBM body, facilitating the steering of the machine.

Since the mucking system of the EPB TBM at the end of the screw conveyor is usually an open atmospheric one, the application area of the EPB technology is limited by the maximum possible support pressure that must be degraded along the screw conveyor to ensure safe advance. As a rule, this is a maximum of around 3-4 bar, provided that the muck is sufficiently cohesive or plastic to form a kind of soil-plug in the screw. With higher support pressures like in this case (6-8bar), the option was to foresee an extended screw conveyor, whereby the mucking could continue by means of an existing conveyor belt. This arrangement has been used in several TBMs in the last 40 years, including the Channel Tunnel TBM and more recently in Cepav 2 project in Italy. A further measure to extend the application area of a classical EPB TBM would be attaching a so-called slurryfier-box to the screw outlet (Figure 5), which acts as a kind of mechanical plug, but requires a slurry circuit with all the necessary components (pumps, separation, etc.). The mucking would then be enclosed within the slurry-pipe system, which means that it could compensate for the risk of unexpectedly extremely high support pressures, but also, very important for the snowy 2.0 projects, serving as a protection in case of encountering asbestos.

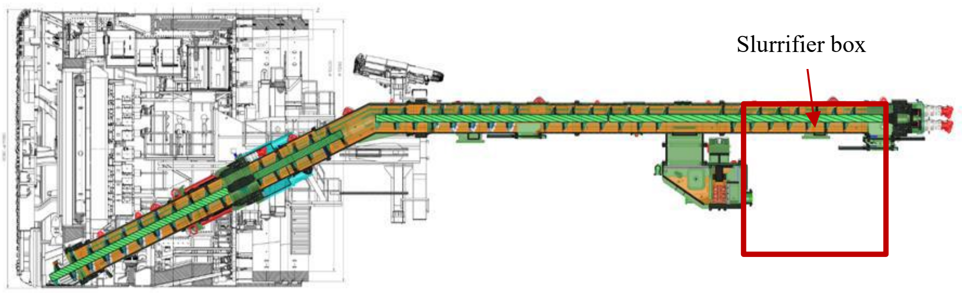

Figure 5. TBM#4 circuits, extended screw conveyor and slurrifier box

If the bentonite-slurry is only added to the slurryfier box at the end of the screw, mining can run as a classic EPB advance and foam can also be added to the muck to reduce the risk of clogging.

For the reasons stated above, an EPB TBM with additional screw conveyor section and a slurryfier box was considered as the best option. The selected TBM#4 can also operate in full open mode with reduced overcutting while excavating the Marica Adit, before to enter the LPFZ, giving an extraordinary wide range of flexibility depending on the different ground conditions (Figure 6).

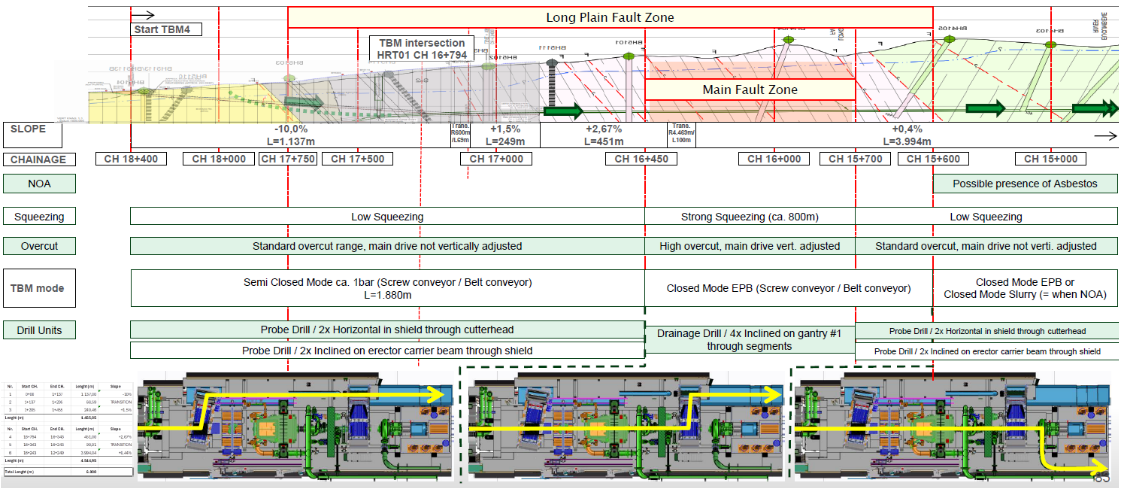

Figure 6. TBM#4 different operating modes across the LPFZ excavation.

Other advanced features have been implemented in the TBM#4 to minimize the risk associated with crossing the LPFZ:

- Integrated hydrodemolition systems, both static and "on-the-go", mounted on the shields. Based on the records of the COCIV Project (Italy), where Hydrodemolition system was installed in two EPB TBMs, activation of the Hydrodemolition on the go can reduce the TBM thrust up to 40%. Moreover, the Hydrodemolition “static” is effective in case of major events or very long TBM stand by time;
- Front active articulation, to improve the steering capability;
- Possibility to disassemble the machine within the tunnel without the need for a dismantling chamber, thanks to the presence of a sacrificial shield which ensures safe operations. This feature is particularly important in case the TBM will need to be disassembled within the LPFZ or in the following region, where there is a risk of asbestos presence.
- In-operation maintenance; a redundant number of filters has been installed, allowing replacements to be carried out without halting TBM operations.

- Special attention to design of the cutterhead, including selection of excavation tools and wear protections. The cutterhead structure was reinforced compared to previous designs;
- Real-time monitoring systems for ground convergence and shield contact pressures;
- Enhanced face conditioning system, to lubricate excavated material and minimize the risk of clogging and bentonite shield lubrication system to reduce friction with the ground and avoid blocking of TBM;
- High-powered main drive with a two-stage reduction system, enabling high speeds to operate in hard rock and very high torque at low cutterhead rotation speeds to operate into the fault zone;
- Back-up system designed to allow the opening of a bypass tunnel, if necessary, without disconnecting or dismantling the back-up structure.

6 DESIGN OF A COMBINED DRAINAGE SYSTEM

As demonstrated by Lombardi Group's analyses conducted and further confirmed by independent assessments carried out by ARX, in areas of moderate/high permeability, the TBM's characteristics—exceptional—would not be sufficient on their own to ensure a restart after prolonged standstills. The face extrusion induced by hydrostatic loads would be excessive after 12hours of TBM stop. Then, a complex drainage system was discussed and introduced as a further remedial action to reduce ground pressures on the TBM both at the tunnel face and along the TBM shield. The main effect of drainage is a reduction of the hydraulic head within the region of the tunnel. Timely installation of drains with respect to TBM advance rate translates in lower water pressures and smaller seepage forces within the rock mass, resulting in smaller total pressures on the machine. The key objective was to identify an execution method that could be implemented with minimal risk of interference with the TBM's advance. As demonstrated by the numerical model, the only reliable condition for successfully overcoming the LPFZ is to maintain as much as possible continuous and uninterrupted TBM progress. Therefore, introducing additional operations (such as the installation of drains) during the progress by stopping excavation was inherently contradictory to this principle. Consequently, a dual-system approach was adopted.

6.1 *Longitudinal drillings from the surface.*

From one side, two 1500mt long drainages performed from the surface by controlled guided drilling and parallel to the tunnel alignment, at a distance of approx 6m from the lining, can be drilled in advance of TBM excavation. They will be activated by means of additional short drills performed from the tunnel, in a second stage, through the segmental lining before crossing the fault zone area.

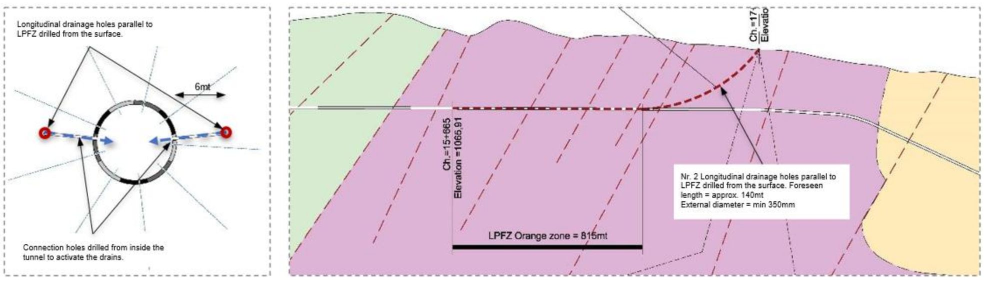

Figure 7. Longitudinal drainages from the surface. Connection scheme with the tunnel for their activation.

Clear beneficial effects have been predicted for this configuration by DJV (face extrusion reduced to more workable values) and ARX (both reduction of face pressure and thrust required after one week stop still lower than maximum machine thrust). The detailed results in terms of jamming risk/required thrust and tunnel face extrusion are recalled in the Figure 9 below (case A) comparing the convergencies with/without the two long drains. Although non-negligible face extrusions still develop after few days of stop, the comparison with the maximum pressure on the machine head in case of constrained extrusion show large pressure reductions compared to the base case. Constrained extrusions could be dealt by means of a limited retraction of the excavation head (e.g. not greater than 10cm), combined with excavation of the tunnel face with no TBM advance. In this sense, overall constrained extrusions in the order of 20cm appear realistic and the relevant face pressure that is obtained appears to be compatible with the TBM exceptional thrust. The innovative and challenging method adopted for the execution of these long drains was developed based on successful experiences in the oil & gas sector—practices that are less commonly applied in the construction industry. However, this is the first time it will be implemented in conjunction with a TBM excavation. If successful, it could pave the way for new approaches to mechanized tunneling in poor ground conditions.

6.2 *Radial drillings from the machine, without stopping TBM#4 excavation*

On the other side, 2 x additional 80mt long radial drainages to be executed from the machine itself, every approx. 20mt of advance are foreseen during excavation. To prevent TBM stoppages the drilling rigs are installed on special sleeves which allow drilling two drains in parallel while the TBM is moving. Because of the overlapping, the effect of combining this setup with the 2 longitudinal drains @ 20 m will permit to have always at least 4 drains from the TBM and the 2 longitudinal ones, for a total of 6 active drains at every tunnel meter, active for more than 5-7 days. This system would also require special segment rings. A special triplet of rings is foreseen every 20 mt to permit the radial drillings in 4 identified fixed location not interfering with any of the multiple TBM equipments. The rings of each triplet are composed by 9 special precast segments already prepared with holes, so to avoid the risk to damage the reinforcement during the perforation. Special reo cages are assembled around the holes to compensate the altered stress distribution. Each of the ring of the triplet is different from the other two.

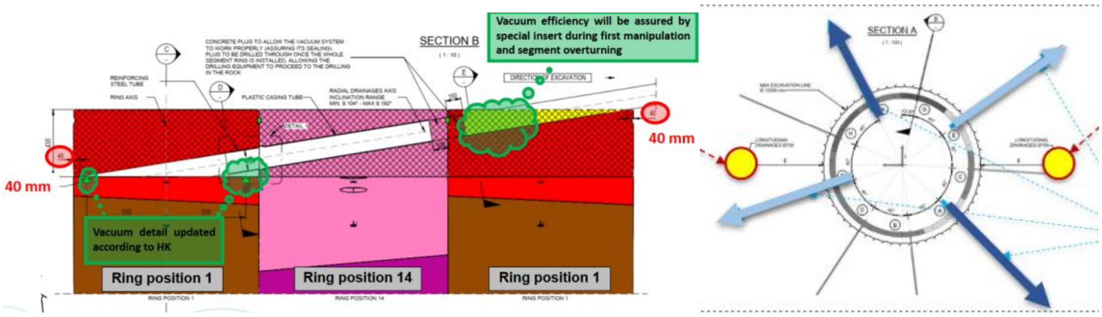

Figure 8. Special ring triplet detail for radial drillings and section view of the 4 selected drill locations.

Figure below shows how the required advance thrust is reduced markedly after drains installation, which is a key condition to allow for machine restart, which would otherwise prove non-feasible in the absence of drains. A comparison with the latest HKN nominal thrust (157MN) shows that additional drains would be required besides the pair of longitudinal drains to allow for normal operation of the TBM, also for continuous advance.

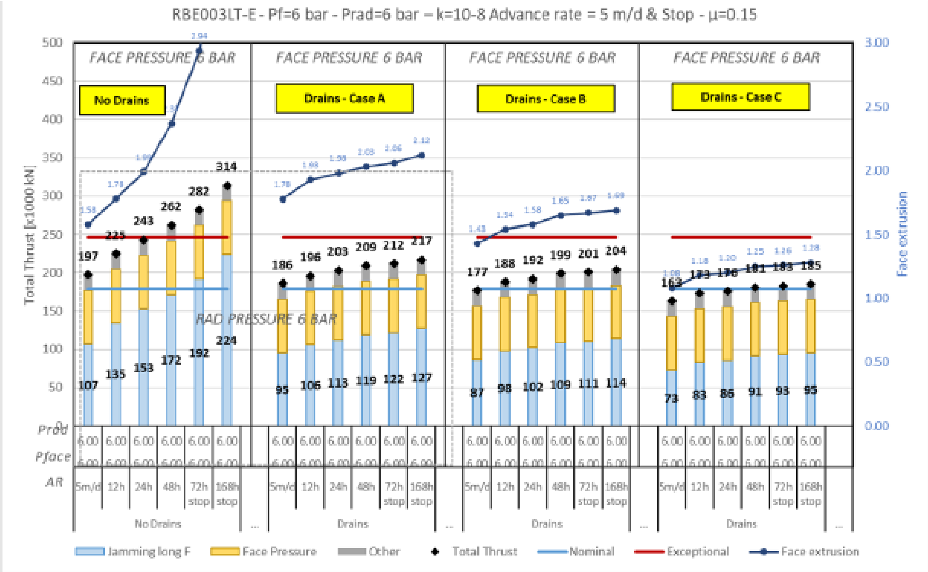

Figure 9. Summary of the results with/without drains. Assuming TBM advance 5mt/day, permeability k=1*10-8m/sec, pressure 6bar. Case 0= no drains Case A= long drains only Case C = long + radial drains.

It is worth remembering all results recalled so far are relevant to a case among the most challenging within the LPFZ, which is the result of an unfavourable combination of permeability and strength rock mass properties. For various other sections of the LPFZ, TBM operation is expected to be less problematic, for example for the excavation in rock masses with lower permeability (e.g. lower than approx. 5x10-9m/s), where the pair of longitudinal drains is expected to be sufficient. The adoption of a mechanised excavation approach could then be combined with a procedure to guide the definition at site of the most appropriate drains set-up, in particular the number of drains to be installed from the TBM in addition to the pair of longitudinal drains. Local ground conditions, known on the basis of the recent additional boreholes, probe holes and the drilling records from previous drainage installation would be the input data needed for this scope.

7 CONCLUSION

The excavation of the LPFZ using a TBM represents a highly challenging operation, whose success relies on three key actions, as outlined in this presentation: first, achieving the most detailed possible understanding of the geological conditions, which in this case was made possible by two directional boreholes drilled parallel to the entire critical section of the LPFZ; second, the design of a TBM specifically tailored to these conditions, involving top-tier international suppliers and equipped with the most advanced available technologies; and third, the implementation of an innovative associated drainage system, capable of reducing pressure on the shields, thereby extending the allowable machine standstill time under worst-case conditions to approximately one week—before pressures exceed the TBM's thrust capacity. Furthermore, the use of mechanized excavation under such extreme conditions contributes to increase the safety on site and represents a further advancement in the application of TBM technology, while simultaneously reducing both construction time and costs.