CHALLENGES IN SMALL DIAMETER TBM TUNNELLING ON THE ERYRI PROJECT IN WALES

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ABSTRACT: National Grid Electricity Transmission Plc's will remove a section of overhead line and replace it with electricity cables buried in a tunnel passing under the Dwyryd Estuary.

HOCHTIEF UK was awarded the contract to construct a 3.3 km long tunnel with an internal diameter of 3.5 m together with two shafts, one new and one modified sealing end compound, two headhouses and the installation of 12 power lines with a total length of 43 km.

TBM excavation works will mainly be conducted in stable rock formations. Only at the beginning of the tunnel drive and under the estuary will the TBM pass soft ground / mixed face conditions. In addition, some known fault zones with a limited extent will be passed during the TBM drive.

Soft ground conditions necessitate active face support to ensure stability during excavation. High overburden with high water pressure in combination with coarse ground conditions in the soft soils under the estuary require the selection of a Slurry-TBM to cope with the expected ground conditions.

Stable rock conditions allow interventions into the excavation chamber for cutter tool control or exchange under atmospheric conditions. In soft soils which require active face support, an intervention must be done in compressed air environment.

During the design phase of the tunnel and the TBM, all reasonably practicable measures have been considered to minimize the risk of hyperbaric exposure. The "Work in Compressed Air Regulations 1996" (WiCAR) allows a maximum overpressure for work in compressed air of 3.5 bar. As the risk of hyperbaric exposures cannot be entirely eliminated and a foreseeable risk of hyperbaric exposure in combination with high water pressures remains, HOCHTIEF had to seek for a regulatory exemption to deviate from this pressure limit and to get approval for high pressure compressed air (HPCA) with a maximum overpressure of close to 6 bar as a contingency if the TBM has to be stopped in the soft soils and further excavation is not possible without works in the excavation chamber.

1. INTRODUCTION

"In front of the tunnel face it's dark!" – Tunnel construction is generally a challenge because there's uncertainty around what might be encountered along the tunnel route. Site investigations are always merely local punctures into the ground, and no matter how dense the pattern of penetrations is set, most of the tunnel route remains an interpretation of the geologist.

Safety plays a crucial role in mechanized tunnel construction, regardless of its size. However, small tunnel diameters, which have increasingly appeared in the recent years in power tunnel construction, pose additional challenges and hazards due to restricted space, especially in works involving the excavation chamber at the tunnel face. These hazards must already be identified and accounted for during the various planning stages of a project, to minimize hazards.

2. PROJECT OVERVIEW

The Eryri Project in the Eryri National Park in Wales aims to reduce the visual impact of National Grid Electricity Transmission Plc's (NGET) overhead line across the Dwyryd Estuary from Penrhyndeudraeth to Cilfor close to Porthmadog. The project includes the removal of approximately 3 kilometers of overhead line and 10 pylons, the construction of a 3.4 km long tunnel under the Dwyryd estuary, the installation of 43 kilometres of cabling. It further includes building of two headhouses, constructing a new sealing end compound, and reconfiguring an existing one.

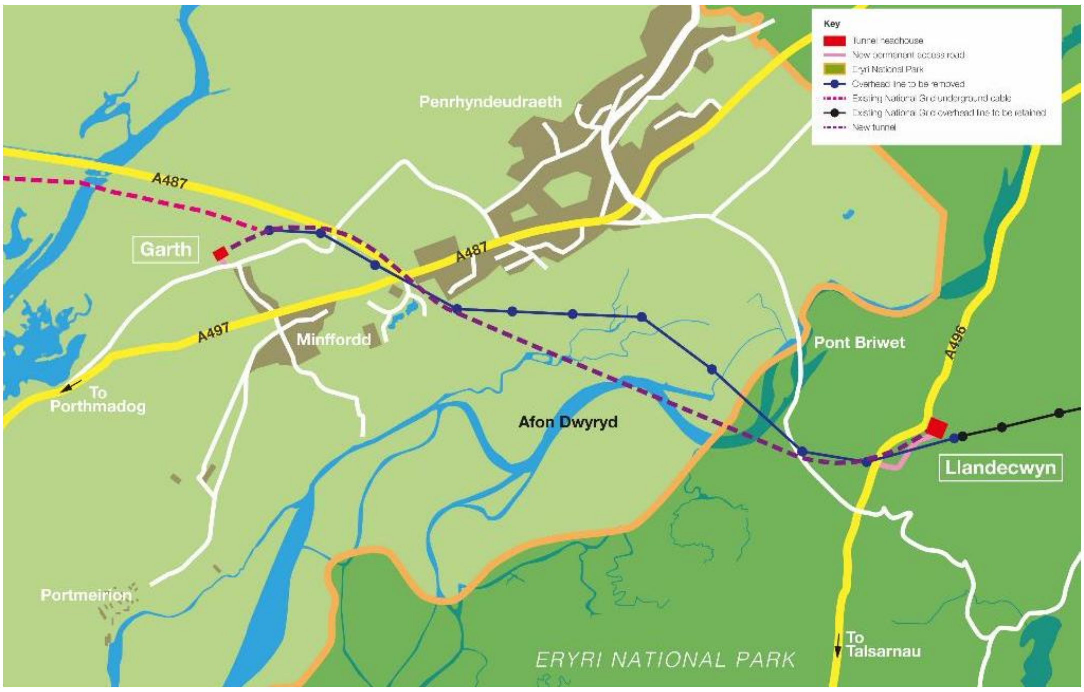

Figure 1: geotechnical long section

3. TBM SELECTION

TBM selection followed the 2022 "Recommendations for the selection of Tunnel Boring Machines", published by the DAUB German Tunnelling Committee (ITA-AITES).

3.1 TUNNEL ALIGNMENT AND GEOTECHNICS

The segmentally lined tunnel has an internal diameter of 3.5 m and accommodates 12 number high voltage power lines of 400 kV.

To avoid maintenance works in the tunnel during its operational stage, the Eryri Project's tunnel alignment was selected under consideration of operational aspects including a pumping station at the Cilfor reception shaft. Consequently, the tunnel continuously slopes downward from the Garth launch shaft, which is located close to the village Minffordd to Cilfor reception shaft on the opposite side of the Dwyryd estuary.

Initially, the tunnel follows an approximate 4% downhill tunnel gradient to gain sufficient cover to pass beneath the railway line which will be crossed at chainage 0+266 m. Past the railway, the tunnel gradient changes to 2.375% downhill for another 963 meters. Thereafter, it crosses the estuary with a slight downward gradient of 0.445% for the remaining tunnel section length of 2.110 m to the Cilfor reception shaft.

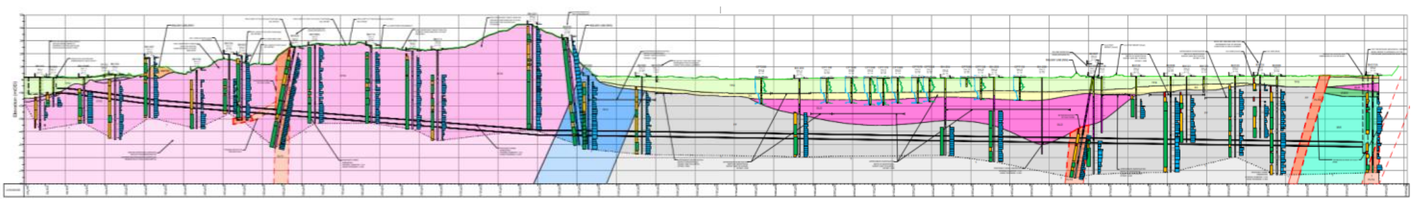

Figure 2: geotechnical long section

Other requirements for the vertical alignment were a minimum overburden between the tunnel crown and the railway line as well as a safe distance to the riverbed.

Stable rock is anticipated for 2,958 meter (89.15%) of the total 3,318-meter drive, specifically for the Dol-Cyn-Afon Formation (DYN), Ffestiniog-Flags Formation (FF) and Maentwrog Formation (MW). These formations are mainly shale formations with a characteristic UCS of 30-50 MPa.

The remaining tunnel sections of 360 meters (10.85%) are expected to consist of soft soils or fault zones. The following sections containing soft soil or fault zones were identified during geotechnical investigation programs that have been carried out before and after contract award:

The first 50 meters at the start of the tunnel drive where the TBM will excavate through the soft soil layers of the Tidal Flat Deposits (TFD).

A section of approximately 80 meters in the known fault zone between chainage 540 and 620 m.

A section of approximately 180 meters under the estuary in the Fluvioglacial Deposits (GLD) from chainage 2,470 to 2,650 m.

A section of approximately 50 meters in the known fault zone around chainage 3,180 m.

Although the majority of the tunnel drive is classified as competent rock with stable ground conditions, the short tunnel sections with unstable ground conditions - a combination of soft soils and high water pressures - are decisive for the TBM type selection.

Active face support must be applied to the excavation face in these sections to guarantee face stability during the tunnel drive. For this reason, an open mode hard rock TBM could not be considered suitable for the Eryri Project and a closed mode TBM had to be chosen.

3.2 TBM TYPES

Active face support can be achieved by pressurizing the excavation chamber to counteract the acting face pressure, which consists of an earth pressure and a groundwater part. Three types of closed mode TBMs were compared to find the best solution for the Eryri-Project.

Earth Pressure Balanced Shield (EPB)

Face support of an EPB-TBM is activated by the excavated muck in the excavation chamber. It will be controlled by adjusting the thrust ram advance speed and the screw conveyor speed, which together determine the speed of muck removal.

Slurry Shield (SLS)

In a Slurry-TBM, face support is applied by the slurry in the excavation chamber. The pressurized section of the TBM is isolated from the atmospheric part of the tunnel by a pressure bulkhead. A second bulkhead with an opening in the bottom separates the excavation chamber from the working chamber. Compressed air will be injected into the working chamber to pressurize the surface of the slurry. Following the principle of a communicating tube, the slurry in the excavation chamber will be pressurized as well. The air bubble pressure in the working chamber can be precisely adjusted and control the required support pressure at the face.

Variable Density Shield (VDS)

The VDS-TBM is a combination of both TBM types. Due to the TBM's small size and the need for additional installations in the TBM shield, this option was not pursued further.

If an intervention into the excavation chamber becomes necessary (e.g. for inspection or repairs), the pressurizing medium - slurry or muck – must be (partially) removed, and the opened face stabilized and supported by compressed air. Thus, the following factors have been identified as the main decisive factors for the final TBM selection:

Coarse ground conditions under the estuary.

Ground investigations of the Fluvioglacial Deposits under the estuary revealed coarse ground conditions. The particle size distribution (PSD) is at the limit of the operational range of a slurry TBM and outside the operational limit of an EPB TBM.

High water pressure and resulting face support pressure in soft soils

Although the alignment has been optimized by raising it approximately 12 meters - thereby reducing the water pressure by 1.2 bar- calculations for compressed air interventions still indicate a maximum required support pressure of nearly 6 bar under worst conditions, which occur during the passage of the estuary within the Fluvioglacial Deposits. Again, while a slurry TBM can deal with this situation, an EPB TBM is not suitable for such conditions.

3.3 FINAL TBM SELECTION

After detailed evaluation of all important factors, the final decision was made for in favour of a slurry TBM. During the TBM tender process, a TBM was found, which had previously successfully excavated a tunnel in Singapore under comparable conditions.

Figure 3: Eryri-Project Slurry-TBM

4. TBM DESIGN

Most of the required technical specifications for the Eryri Project were already met by the selected TBM. Only minor modifications were necessary during its refurbishment. These include (1) the integration of two stabilizers to avoid unintended roll of the machine, (2) a new tail shield, which considered the requirements of the differences between both project regarding the segment design, (3) the integration of a refuge chamber, and (4) the installation of a powerful dewatering system for the tunnel and TBM due to the downhill alignment

5. MINIMISING HYPERBARIC EXPOSURE

During refurbishment and modification of the TBM, the focus was put on minimizing hyperbaric exposure due to the expected high face support pressures.

Although the expected geology permits free-air interventions under atmospheric conditions for most of the drive, there remains a foreseeable risk that the TBM may have to be stopped in soft soils with coarse ground conditions and high-water pressure, necessitating a hyperbaric intervention.

The following paragraphs give an overview of design modifications of the selected refurbished TBM to minimize hazards caused by hyperbaric exposure:

5.1 OPTIMISATION OF CUTTER HEAD DESIGN

The existing cutter head of the selected TBM was already well-designed for the project purposes. Thus, only small modifications were required. HOCHTIEF opted to install 18-inch disc cutters instead of the originally planned 17-inch version to allow for longer operation of the disc cutters due to the higher wear limit. Due to geometric constraints, the four central double disc cutters were kept at 17 inches. These disc cutters were positioned slightly forward so that all discs run on the same level in front of the cutter head's steel structure. Additionally, wear protection plates for the cutter head structure as well as the position of the wear detection pins have been optimised based on lessons learned from earlier projects.

5.2 OVERCUT MONITORING SYSTEM

An overcut monitoring system was installed in the crown part of the middle shield to measure the annulus gap between the excavated ground and the shield skin without requiring chamber interventions. The overcut monitoring system comprises a small cylinder, which will be hydraulically extracted from within the intermediate chamber in the atmospheric part of the shield. By measuring the cylinder's stroke length, the ´TBM crew can accurately evaluate the overcut.

5.3 TELESCOPIC CAMERA SYSTEM

It has been best practice on some TBMs in earlier projects to do a first check of the face and the condition of the excavation tools by a camera in the excavation chamber. Since the cameras have been installed in a fixed position in the submerged wall area, they could only monitor a small section of the cutter head or the excavation face. On larger diameter TBMs, but not on machines with this small diameter, it was also possible to install telescopic cameras which are parked behind the submerged wall during normal excavation. In the event of a slurry drawdown after stopping the TBM, the camera was extended and the stroke was sufficient to move the camera directly to the face and the excavation area. The camera head also allows for 360-degree rotation and tilting, which enables the operator to focus on specific details in individually selected areas (e.g. for face evaluation or cutter tool checks). Prior to operation, the camera lens is cleaned using water flushing and compressed air drying. HOCHTIEF decided to integrate a telescopic camera on such a small diameter TBM for the first time. Together with the TBM supplier, one of the two existing horizontal drill ports was finally found to be a suitable location for the installation of the camera.

5.4 FIXED PROBE DRILL

The existing TBM already came equipped with inclined probe drill ports for exploration drilling around the shield body. The installation of a drill rig was foreseen on the segment erector. Lessons learned from earlier projects showed that the transport of the drill rig and its complete hydraulic power pack via the segment feeder through the backup of the TBM to the erector location is very narrow, complicated, and time consuming. Therefore, HOCHTIEF decided to find a fixed position for the drill rig and hydraulic unit on the backup behind the TBM. An additional short bridge section was designed and fabricated to allow for drilling at approximately the 11 o'clock position. With an incline of 7°, this allows for geological exploration ahead of the excavation face. To facilitate this an additional probe drill port was integrated into the shield body of the middle shield.

5.5 BEAM INTEGRATION

During excavation of the Cilfor reception shaft, a huge number of large boulders was found within the soft soils in the transition zone between the Fluvioglacial Deposits and the rock head. The quantity and size of the boulders led to a re-evaluation of the geotechnical conditions beneath the estuary, where the same Fluvioglacial Deposits intersect the tunnel's excavation cross-section. There is a foreseeable risk that similar boulders will be encountered in the transition zone between both layers. These have the potential to impact tunnelling operations or cause damage to the TBM and its cutting tools.

Following discussions between HOCHTIEF and National Grid, it was decided to implement the geotechnical exploration system BEAM into the TBM. This system can be installed even on a running TBM - without installation works on the cutter head. The BEAM system provides a geological forecast ahead of the tunnel face. This enables the TBM operator to better adapt machine parameters depending on expected ground conditions and changes in geology.

5.6 OPTIMISATION OF CUTTER TOOLS

In addition to the BEAM integration, it was also decided to switch from the ring-type disc cutters used successfully thus far to monobloc disc cutters for the estuary section, which are expected to be more durable under the expected ground conditions and the presence of boulders.

6. (HIGH PRESSURE) COMPRESSED AIR WORK

Although everything reasonably practicable has been done during design of the tunnel and design and fabrication of the Tunnel Boring Machine, there remains still a foreseeable risk for hyperbaric exposure.

6.1 PREPARATION TBM AND AIRLOCK SYSTEM FOR HYPERBARIC EXPOSURE

As the risk of hyperbaric exposure could not be entirely eliminated, measures had to be considered to allow entry into the excavation chamber under hyperbaric conditions. Due to the tunnel alignment and the water table above the tunnel, only the first section of the tunnel drive would allow for low pressure compressed air work (LPCA work). LPCA work in this aspect is defined as work which is covered under the 1996 "Work in Compressed Air Regulations" (WiCAR), where the maximum overpressure remains below 3.5 bar.

In addition to these local regulations and its guidance, the international norms EN 12110 ("Tunnelling Machines – Airlocks") and EN 16191 ("Tunnelling Machines") provide clear instructions for both the design and the fabrication of the TBM, airlocks and associated hyperbaric equipment. Both norms are currently in the revision process and have the status of FprEN 16191:2026, FprEN 12110-1:2026 and FprEN 12110-2:2026, where part 1 deals with compressed air works utilising compressed air as pressurising and breathing medium and part 2 deals with non-air breathing mixtures and saturation techniques under high pressure compressed air. Together with report No. 10 of the ITA Workgroup 5 ("Guidelines for good working practice in high pressure compressed air"), these documents build the framework for the requirements on hyperbaric works on the Eryri-project.

In collaboration with a specialist subcontractor for high pressure compressed air work and the contract medical advisor advising the contractor on all aspects of occupational health relating to the work in compressed air under the WiCAR – HOCHTIEF, acting as the Compressed Air Contractor, planned the works in the excavation chamber using high pressure compressed air.

For high pressure compressed air (HPCA) work, Tri-Mix (a mixture of oxygen, nitrogen and helium) will be used as breathing gas whilst pressurized air is still the environment where HPCA works will be carried out. There are two options for HPCA interventions. Non-saturation mixed gas interventions only allow for short periods of exposure in high pressure compressed air environments, followed by long decompression times without saturation of the nitrogen dissolved in the mixed gas worker's body. The second alternative is HPCA utilizing a saturation technique where the nitrogen in the mixed gas worker's body is completely dissolved to saturation. This approach permits longer working periods in the excavation chamber, as the mixed gas worker remains under overpressure in a surface habitat between the working shifts.

Saturation works are planned when it is foreseeable to carry out extensive work in the excavation chamber under high pressure. It also requires a transport shuttle between the airlock of the TBM and the living habitat of the saturation worker on surface. The shuttle is kept under pressure during transfer to and from the TBM, and minimum geometrical requirements are set out in the EN 12110 part 2. Due to the small size of the tunnel on the Eryri-Project, saturation works are not an option and only non-saturation mixed gas works can be carried out if HPCA work occurs.

6.2 EXEMPTION PROCESS

HPCA work is foreseen only as a contingency if all previous measures fail and an intervention into the excavation chamber cannot be avoided to proceed with the tunnelling works. For HPCA work, HOCHTIEF was required to obtain an exemption to exceed the 3.5 bar pressure limit of 3.5 bar specified by WiCAR.

The exemption process mandates proof that all reasonably practicable measures have been taken to avoid or minimize HPCA risks. It further requires proof that all necessary preparation works have been carried out under the before-mentioned regulations, norms and associated guidelines. A safe system of work must be established under consideration of specialized personnel, the correct selection of special equipment and procedures for regular activities under HPCA, as well as evacuation and emergency scenarios. Emphasis is placed on the geometrical restrictions of a small diameter of TBM impacting work in HPCA, whilst wearing a full-face mixed gas breathing mask and being supplied with breathing gas from umbilical.

Gas calculations were performed to evaluate the required amount of breathing gas under worst-case scenario conditions. Primary gas supply, secondary gas supply, and emergency gas supply pipework will be installed between the gas bottles and the mixed gas operator panel, where the mixed gas supervisor controls the supply of breathing gas to each individual mixed gas worker. In the pressurized environment, breathing gas is supplied via umbilical – flexible hoses which allow the mixed gas worker to move from the airlock to the work location in the excavation chamber and back. Compression and decompression of the mixed gas workers will be done following the guidance in the documents as mentioned before. Decompression tables must be selected, and their application validated by an independent third-party hyperbaric expert. Occupational health surveillance by extensive fit for work medical checks is to be carried out by the appointed doctor before any work in HPCA can be commenced. During HPCA operations, mixed-gas workers maintain constant communication with the mixed-gas supervisor on the mixed-gas operation control and communications panel. Once back in the airlock, decompression starts, and the lock attendant takes over monitoring and control of the intervention team as soon as the mixed gas breathing masks will be taken off on the first pressure level.

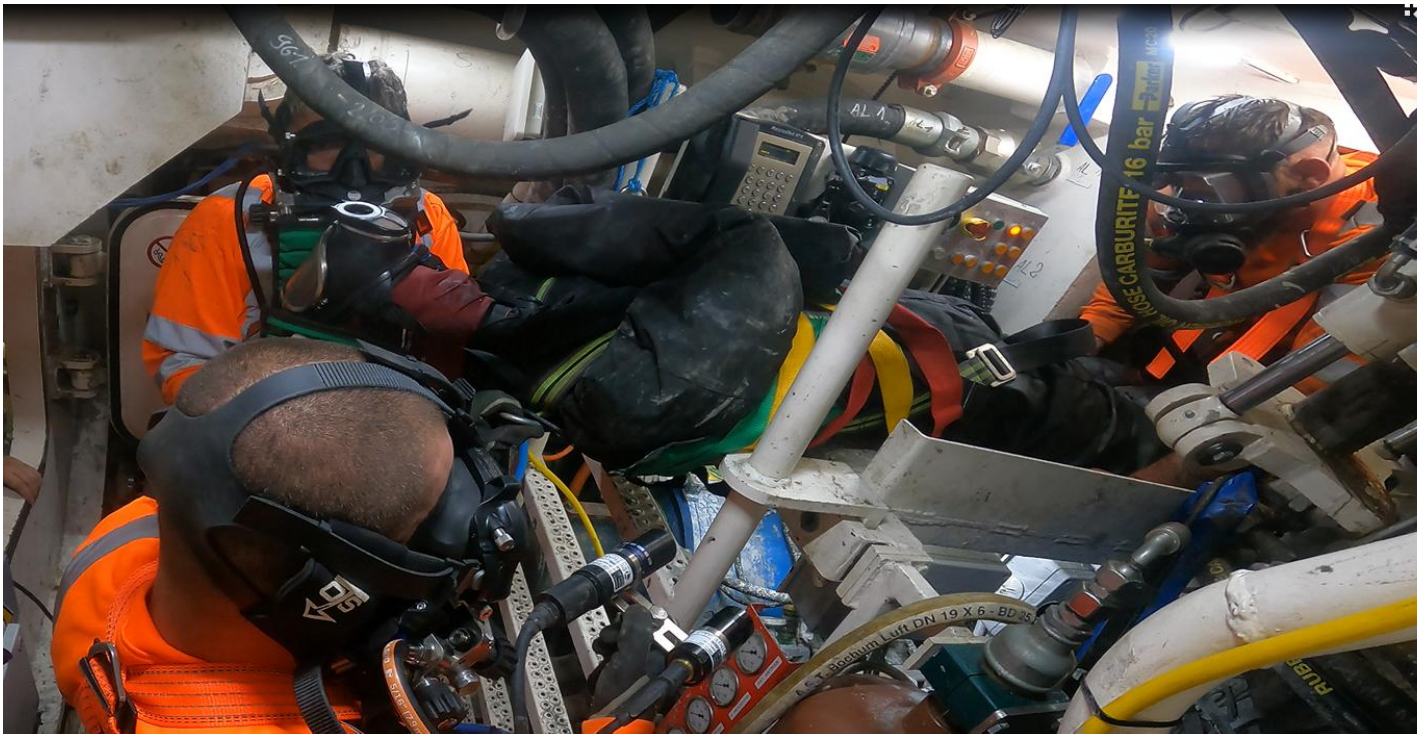

Figure 4: Rescue exercise "evacuation from excavation chamber"

Health monitoring proceeds after decompression when the intervention team is back to atmospheric pressure. For a duration of three hours, Doppler monitoring will be carried out to evaluate the changes in nitrogen bubble occurrence over time.

High pressure compressed air work is not a regular activity in TBM tunnelling works, and projects seeking regulatory exemption have historically been exceptionally rare in the UK. Thus, the exemption process is difficult and time consuming. This must be factored into the project schedule, with the application process initiated at the earliest possible point in time in the beginning of the project.

7. CURRENT STATUS OF THE PROJECT

After completion of the Garth launch shaft and the TBM assembly, TBM excavation has started in May 2025. As of January 2026, the TBM has successfully completed 2.1 km of the tunnel drive. Two soft soil sections have been passed without any issues and the TBM is currently operating under Dwyryd River estuary. The change in geology between the competent rock of the Ffestiniog-Flag formations and the Fluvioglacial Deposits is expected in approximately 400 m. During the last hundred meters, the TBM has excavated through several short sections where partially sandy material from the Fluvioglacial Deposits was encountered in the tunnel cross-section. The TBM has been halted to facilitate the installation of the second booster pump station of the slurry circuit and will be re-started for its final section of the tunnel drive once installation works are completed.

To date, 24 interventions into the excavation chambers have been carried out to check or exchange cutter tools – all of them under atmospheric conditions. Shortly before reaching the expected soft soil section under the estuary, all tools on the cutter head will be exchanged, independent of their individual wear to further reduce the risk of hyperbaric exposure under HPCA. Despite the exemption process having been initiated over one and a half year ago, the exemption has not yet been granted and further liaison with the authorities is required.

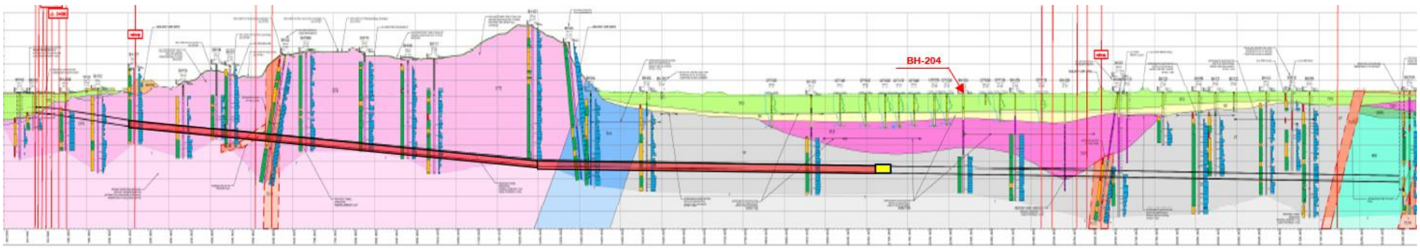

Figure 5: Status of tunnelling works January 2026

8. CONCLUSION

The Eryri Project is making significant progress in tunnel construction, addressing the challenges of unknown underground conditions and the complications that come with small diameter tunnels. Detailed geotechnical assessments and strategic alignment decisions for the Eryri Project have been pivotal in defining the project's approach. This careful alignment of the tunnel path is engineered to meet operational goals while mitigating potential geological hazards, particularly those introduced by softer soil formations and fault zones.

Safety upgrades to the TBM are a central focus, aiming to reduce workforce exposure to the confined space and high-pressure environment of the excavation chamber. More durable cutting tools and cameras that check the tunnel face without needing chamber entry, the project utilises technology to enhance safety.

Preparatory measures for possible high-pressure compressed air work highlight the project's proactive stance in addressing potential hyperbaric risks. By securing regulatory exemptions and adhering to stringent norms, HOCHTIEF demonstrates a thorough and systematic approach to ensuring safe working conditions despite complexities.

Currently, as the project progresses through its critical phases, there remains an emphasis on timely execution and completion. Despite challenges – such as ongoing liaison for exemption clearance – technical and regulatory hurdles are being collaboratively overcome. As tunnel construction continues under the Dwyryd River estuary, the project showcases forward-thinking engineering solutions tailored to specific geotechnical and technical contexts.

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