Two Major Technical Solutions on the Lung Shan Tunnel – Pilot TBM Tunnel Enlargement and TBM U-turn in Cavern

X Monin, L Jeanne*, V Tricot, R B Storry

Dragages Hong Kong Limited, Hong Kong, China

*Corresponding author

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ABSTRACT

On the Liantang / Heung Yuen Wai Boundary Control Point Site Formation and Infrastructure Works – Contract 2 in Hong Kong SAR, Dragages Hong Kong Limited have proposed and implemented two major technical solutions and construction methodologies to overcome the programme constraints and the geotechnical challenges of the 4.8 km long Lung Shan Tunnels section.

1. **Pilot TBM Tunnel Enlargement:**

Due to a tight 350 m horizontal curve, the northern 500 m of the Liantang Lung Shan tunnels comprise mined tunnels of larger span (3m wider internally than the standard two lanes 14.1 m diameter TBM bored tunnel). For programme reasons it was not possible to wait for the 500 m long mined tunnel to be completed before the 14.1 m diameter TBM was launched in the southbound tunnel to bore the 2,400 m long segmental lining standard two lanes tunnel towards the Mid-Ventilation Junction Cavern.

Therefore, the TBM was launched within the horizontal curve, at 200 m from the North Portal, and the 300 m long 14.1 m diameter TBM "pilot" tunnel within the curve had to be subsequently enlarged to its final size, using mined tunneling technique along with advanced construction methodology and temporary steel gallery.

2. **TBM U-turn in Cavern:**

In addition, to reduce the geotechnical risk of tunneling in faulted ground and to secure the Project programme, the TBM drive was significantly lengthened, from originally 1,000 m to 2,400 m per tunnel. Following the completion of the first TBM drive, the TBM was ripped over 100 m within the receiving southbound mined tunnel, from the TBM break-out face to the large size Mid-Ventilation Junction Cavern, where it did a U-Turn towards the short section of pre-excavated northbound mined tunnel for the break-in preparation of the second 2,400 m long TBM drive. Minimizing the extent of TBM dismantling and reassembly, and with the use of a turn table which was redesigned for the occasion, the overall operation took 3 months only, between the break-out date of the first drive and the break-in date of the second drive.

Keywords: Cavern, Pilot TBM, Tuff

1 Introduction

1.1 The Project

The Liantang Heung Yuen Wai Boundary Control Point project comprises the site formation of about 23 hectares of land for provision of the Boundary Control Point (BCP) buildings and associated facilities, as well as the construction of about 11km long dual 2-lane Connecting Road between the BCP and Fanling Highway. Part of this Project, the Liantang / Heung Yuen Wai Boundary Control Point Site Formation and Infrastructure Works – Contract 2 constructed by Dragages Hong Kong Limited (DHK, a member of the Bouygues Construction Group) mainly consists of the design and construction of a 4.8 km long dual two-lane trunk road tunnel connecting the proposed Sha Tau Kok Road interchange and the Fanling Highway interchange, 49 cross passages, a 300 m long ventilation adit tunnel between the

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mid-Portal and the Mid-Ventilation Junction Cavern, three ventilation buildings, an administration building, and the site formation and slopes works at the South and North Portals. The project reduces the travel times from Fanling Highway to Ping Che area and Heung Yuen Wai, Ta Kwu Ling from 15 and 24 minutes, to 4 and 8 minutes respectively. The road tunnel was open to Public in May 2019.

The geology which consisted of Volcanic Ash Tuff Rock was found extremely variable during the works, from very strong rock (up to 200 MPa UCS) to Completely Decomposed Tuff (CDT), with many sections of faulted ground, geological structures and high-water inflow. A combination of a 14.1 m diameter Earth Pressure Balance Tunnel Boring Machine (EPB TBM), together with mechanical and drill and blast excavation techniques, was adopted to cope with the various ground conditions along the 4.8 km tunnel route. The EPB TBM was used for the construction of the tunnels in the northern section, where several fault zones and valleys were located, while drill and blast technique was mostly used in the more competent rock of the southern section, see Figure 1.

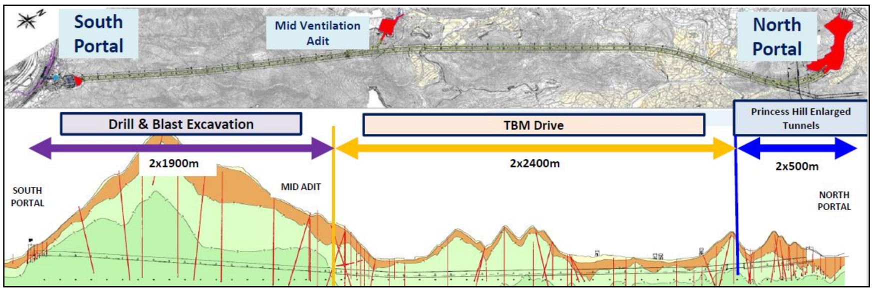


Figure 1: Lung Shan tunnel geology and tunneling techniques

Due to land ownership constraints the northern 500 m section of the tunnels has a curved alignment with a 354 m radius which restricts the sight-line distance of the road users to below the minimum 110 m at 80 km/hr. To overcome this the internal span of the tunnels needed to be increased from 12.6 m, in the standard straight section, to 15.4 m in this curved section to accommodate a widened shoulder which provides the required sight-line distance. Therefore the 14.1m diameter TBM was not large enough to build the tunnel permanently in the first 500 m of the Project from the North Portal, see the blue section on Figure 2.

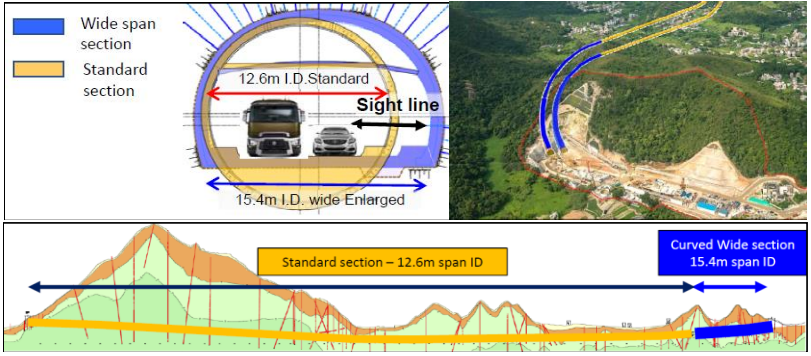


Figure 2: Wider tunnel in the first 500 m long horizontal curve due to sight distance requirement

1.2 Challenging Programme and DHK's Alternative Scheme

Refer to Figure 3 below - in the conforming scheme the full 500 m length of the large span southbound tunnel was completed, before the TBM was launched, which resulted in a very late start of the TBM. Therefore, the TBM drive could only be short (approximately 1 km), could only address the crossing of the first valley, and had to be fully dismantled and reassembled for the second 1 km long drive in the northbound tunnel. Therefore, the second valley and faulted ground section were going to be excavated by traditional drill-and-blast or mechanical method, which DHK also identified as a very high risk for the Project. Finally, there was a programme risk to complete the Project meeting the Project completion date.

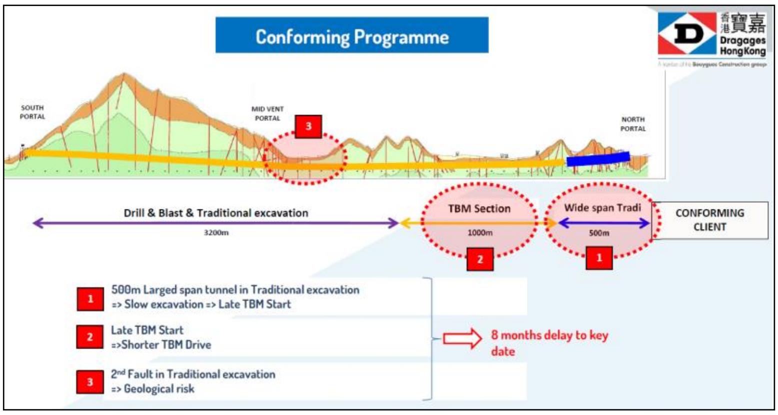


Figure 3: Conforming scheme not meeting the Client’s Project completion date

During the tender stage DHK identified three major objectives to deliver a successful Project to CEDD:

1. How to secure the Client’s Project completion date?
2. How to optimize the use of the TBM?
3. How to reduce the geological risk?

As shown on Figure 4, to meet these objectives DHK developed and proposed the following alternative scheme in their tender submission:

a. The TBM was launched much earlier, as soon as it was getting ready to bore, after 200 m of large span tunnel excavation (instead of 500 m in the conforming scheme)

b. Therefore approximately 300 m of the 14.1 m diameter TBM tunnel became a pilot tunnel to be enlarged afterwards by 5 to 9 m

c. Thanks to the pilot tunnel enlargement methodology presented in the Section 2 below, the TBM could progress ahead along its drive southwards, while the pilot TBM tunnel was being enlarged behind, off the critical path

d. It was also decided to extend the EPB TBM drive from 1 km to 2.4 km length, thus mitigating the highest geotechnical risk of the project which would have consisted of crossing the 2nd valley and faulted ground section using mechanical or drill-and-blast technique in the conforming scheme

e. In addition, using the construction method presented in Section 3 below, the TBM was proposed to U-turn within the Mid-Ventilation Junction Cavern to minimize the time required to start the 2nd TBM drive northwards

f. Finally, thanks to this alternative technical scheme, DHK were able to advance the works by 8 months and to meet the Client’s Project completion key date.

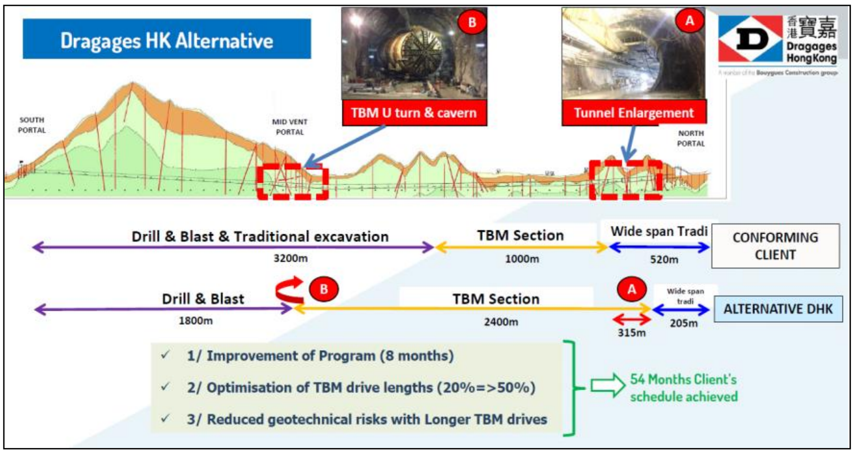


Figure 4: DHK’s alternative scheme with Pilot TBM Tunnel Enlargement and TBM U-turn in Cavern, meeting the Client’s Project completion date

The Sections 2 and 3 below present the construction methodologies used for respectively the Pilot TBM Tunnel Enlargement works and the TBM U-turn inside the Mid-Ventilation Junction Cavern.

2 Pilot TBM Tunnel Enlargement

2.1 Enlargement Works and Objectives of the Construction Method

As shown on Figure 5, the enlargement works of the pilot 14.1m diameter TBM tunnel are massive, in length (approx. 315 m) and in cross section. Considering all construction tolerances, where canopy vaults were required, the excavated span of the enlarged tunnel ranged from 21 m to 23 m and the height from 15.5 m to 16.5 m. With such large dimensions the total excavation area (235 m^2 to 275 m^2) was closer to the scale of a cavern rather than a standard tunnel.

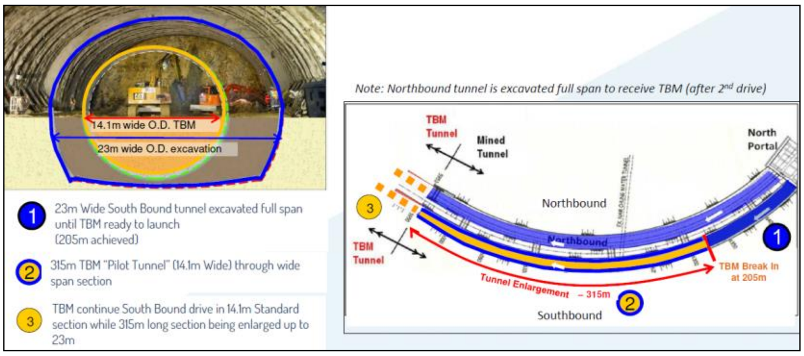


Figure 5: Pilot TBM Tunnel Enlargement Works

A construction method had to be developed to enlarge the pilot TBM tunnel, while meeting the following objectives:

- To maintain 24 hours, 7 days a week, the TBM logistics traffic and utilities during the enlargement works, to continuously supply the 2,400 m long TBM drive ahead, particularly with temporary ventilation, precast segments and pipes delivery, EPB TBM mucking out conveyor belt, temporary utilities, workers' vehicle and pedestrian access
- No restriction to the TBM supply, the enlargement works having to adapt to the TBM cycle, and no stoppage of the TBM was allowed
- Ensure a safe environment, not only for the enlargement works but also to all other workers and plant transiting through the section of enlargement works, such as the TBM crew, maintenance teams, support teams (plant, survey, safety, quality, technical), drivers, MSV, site vehicles and plant, etc.

2.2 Proposed Construction Method and Sequence

It was quickly identified that a temporary steel deck structure was required, on top of which the enlargement works of the tunnel top heading could be carried out, while the TBM logistics could flow underneath it. Several options were considered such as a tailor-made rolling gantry tool, a recyclable shorter temporary steel gallery, or a full-length temporary steel gallery. While the size required for the possible rolling gantry was found too large and unpractical, the option of recycling a short temporary steel gallery as the top heading enlargement works progress was found difficult logistics wise and likely unsafe. Finally, the project team selected the construction method using a full-length 315 m long temporary steel gallery.

Figure 6 shows an overall view of the site set up in the pilot TBM tunnel enlargement area, with the TBM progressing ahead towards the Mid-Ventilation Junction Cavern. The following Figures 7 to 14 illustrate the details of each step of the construction method and enlargement works sequence selected.

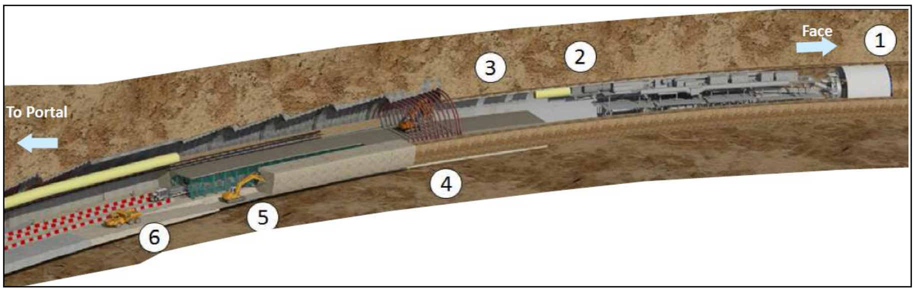


Figure 6: Overall sequence of pilot TBM Tunnel Enlargement works

Step 1 – build the 315m long pilot 14.1 m diameter TBM tunnel, using steel fibre reinforced precast segments (to ease their subsequent demolition), which was a first of that size in Hong Kong. Three rings were indeed instrumented with strain gauges and crack meters to study the behaviour of large diameter fibre reinforced precast segmental rings in comparison with conventionally reinforced precast segmental rings.

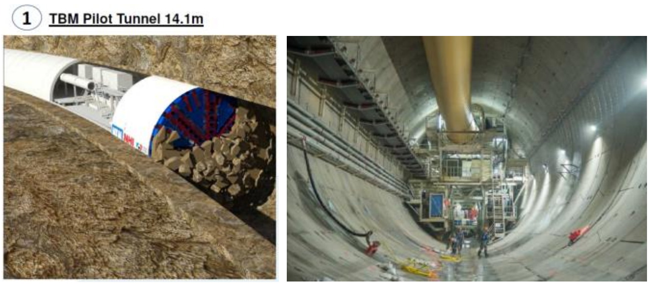


Figure 7: 315m long pilot EPB TBM fibre reinforced segmental lining tunnel

Step 2 – install the arch ribs foundation of the future temporary steel access gallery, the temporary backfills and the temporary utilities required for the TBM (TBM mucking out conveyor, air and water supply pipes, 2.5m diameter ventilation duct and 22kVa electrical cables).

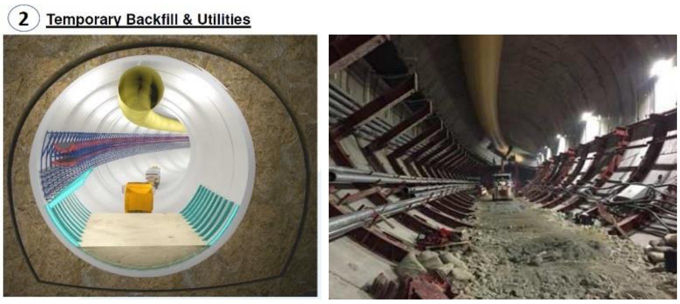


Figure 8: Installation of temporary steel gallery foundation, backfill and utilities

Step 3 – install the 315 m long temporary steel gallery made of mostly universal columns, one bottom arch member and two vertical columns every 3.2m, as well as a deck made of universal columns and sheetpiles. The upper part of the structure is backfilled and dedicated to the top heading enlargement works, while its lower part hosts the conveyor and some utilities on one side, the TBM vehicular access in the middle, and a safe segregated pedestrian access, TBM ventilation duct and other utilities on the other side. The temporary steel gallery was designed by DHK's Designer Atkins China Limited, based on a series of load combinations defined from the detailed planning of the enlargement works.

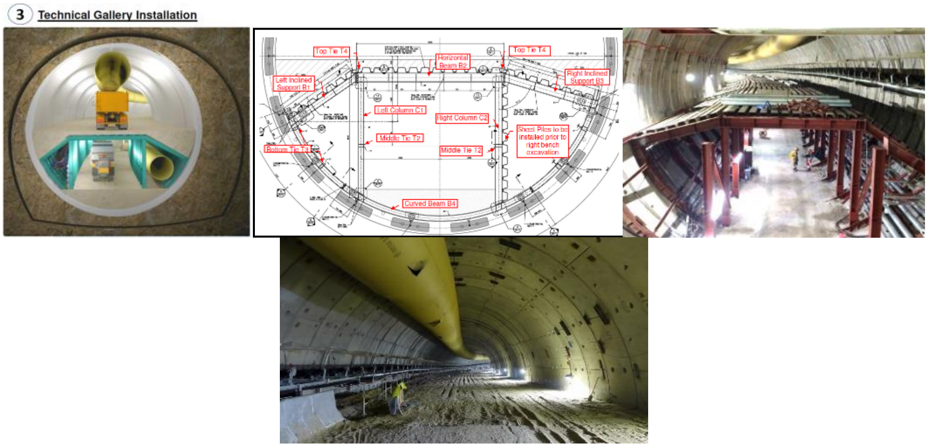


Figure 9: 315m long temporary steel gallery installation and backfill on the deck

A special section of steel gallery of approximately 80 m length is designed and installed at the start of the 315 m long gallery, including a steel ramp to the top side of the deck and an open side span for the traffic and logistics to be able to access underneath the deck of the gallery.

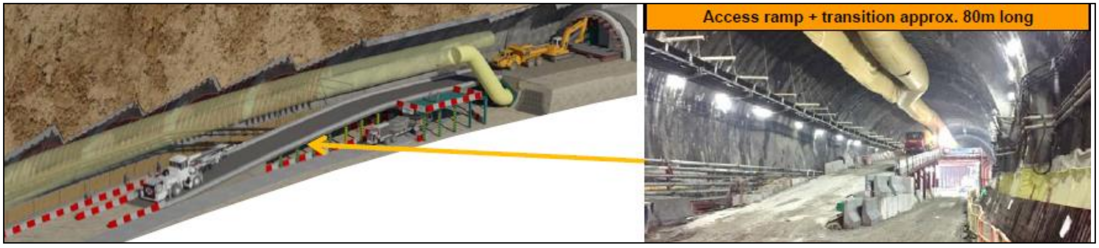


Figure 10: Special gallery section at the start with access ramp and side span vehicle entrance into the gallery

Step 4 – carry out the tunnel top heading enlargement works consisting of a traditional excavation method:

- Pre-excavation probing and grouting to control the ground water inflow into the tunnel
- Installation of canopy vault in adverse ground conditions to strengthen the crown of the excavation
- Demolition of the temporary steel fiber TBM segments using breakers, by round of 1.6m advance being the width of a segment
- Installation of heavy temporary supports steel arch ribs, lattice girders, or rock dowels in better ground conditions, as well as shotcrete at the tunnel crown, walls and face
- At each 1.6 m advance, the cycle of excavation, breaking of segments, temporary support installation was repeated.

Figure 11: Pilot TBM tunnel top heading enlargement works from the top of the temporary steel gallery

The dynamic force induced by the segment pieces falling onto the top of the technical gallery was expected to be significant. To reduce it an impact gantry was designed, fabricated and pulled below the segments being demolished. The impact gantry was composed of many longitudinal supporting beams, a receiving platform at the bottom, as well as sliding beams allowing movement of the whole gantry to its next position, Figure 12.

Figure 12: Special impact gantry preventing the fall of large blocks and reducing the impact load on the steel gallery

Step 5 – following the top heading enlargement, it was then possible to relocate the utilities, the ventilation duct and the conveyor to the upper section of the tunnel, which allowed the partial dismantling of the right-hand side of the technical gallery, as well as the right-hand side bench enlargement, while the construction traffic remained in the middle part.

Figure 13: Relocation of utilities, right-hand side bench enlargement and partial dismantling of the steel gallery

Step 6 – shift the construction traffic to the already enlarged bench on the right-hand side, complete the dismantling of the steel gallery and the bench enlargement on the left-hand side. The enlargement of the pilot TBM tunnel is now complete.

Figure 14: Left-hand side bench enlargement and completion of the steel gallery dismantling

2.3 Enlarged tunnel temporary support

The geology in the section of pilot TBM tunnel enlargement was very variable, consisting generally of rock, partial rock 50/75, partial rock 10/30, or even CDT at crown, see Figure 15.

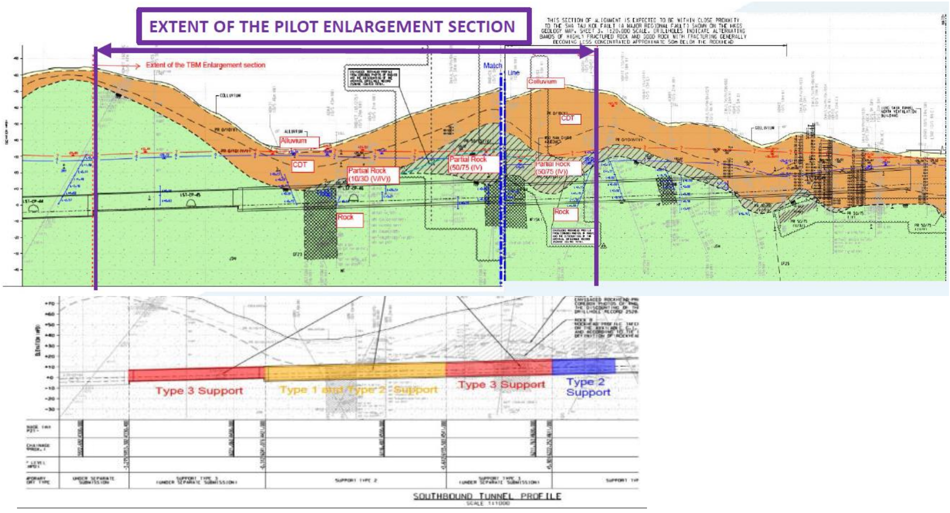


Figure 15 – Geology and temporary support types used for the pilot TBM enlargement works

See Figure 16, we developed 3 main types of temporary support designs, which were used alternately along the enlargement works, according to the ground conditions:

- Type 1 support was made of canopy tubes and steel arch ribs every 800mm, with 300mm shotcrete

- Type 2 support was of similar arrangement, however much lighter, with lattice girders instead of arch ribs

- Type 3 support was made of rock dowels and shotcrete

Pre-excavation probing and grouting were also included in the enlargement works cycle, following the same principles as in the standard mechanical excavation sequence.

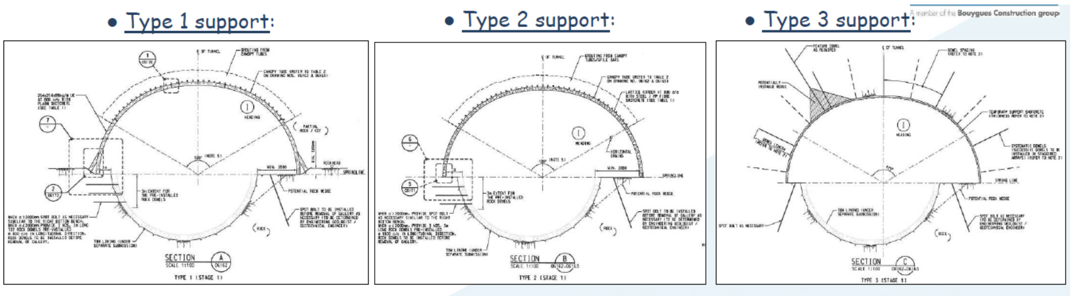


Figure 16: Pilot TBM tunnel enlargement top heading temporary support designs

2.4 Achievement

The TBM pilot tunnel enlargement operation went better than anticipated: as shown on Figure 17, we managed to progress 1 ring per day for the top heading, 1.5 ring and 2.5 rings per day respectively for bench RHS and LHS enlargement. Overall, the enlargement of that 315 m long 14.1 m diameter pilot tunnel took 14 months instead of the 17 months anticipated. Most importantly we managed to carry out these very challenging enlargement works safely, without any disruption to the TBM progress ahead, saving about 5 months on the project critical path, in comparison with having waited for the completion of the 500 m long large span tunnel by traditional excavation means only.

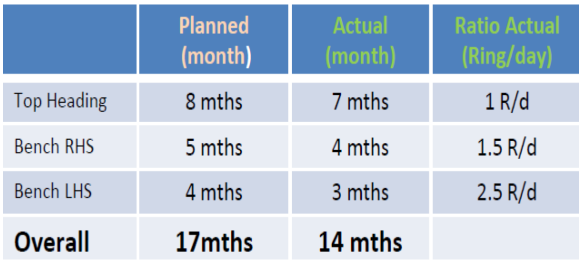
We had also checked other possible TBM alternative schemes:

i. Two TBMs: one TBM of 17 m diameter to excavate the 500 m section of large span tunnels, and one TBM of 14.1 m diameter to do the rest of the drives, or

ii. One hybrid 17 m diameter TBM, which could change diameter to 14.1 m, after 500 m of excavation

Those alternative TBM schemes would have introduced more programme risks (risk of insufficient TBM torque of what would have been the largest TBM in rock in the world and in a tight horizontal curve; technical first of significantly modifying the cutter head and shield underground, with the need of a local cavern for the operation), would have been less cost effective, and less efficient for the Project critical path.

We trust that the 14.1 m diameter TBM pilot tunnel and its subsequent enlargement solution selected was the best technical scheme for the Liantang Project.



	Planned (month)	Actual (month)	Ratio Actual (Ring/day)
Top Heading	8 mths	7 mths	1 R/d
Bench RHS	5 mths	4 mths	1.5 R/d
Bench LHS	4 mths	3 mths	2.5 R/d
Overall	**17mths**	**14 mths**	

Figure 17: Pilot TBM tunnel enlargement production rates

3 TBM U-turn in Cavern

3.1 TBM U-turn Methodology Objectives and Early Engineering

As shown on Figure 18, three main TBM movements were required for the TBM U-turn operation across the Mid-Ventilation Junction Cavern, between the first and the second TBM drives:

- a longitudinal sliding in the southbound tunnel, from the break-out face to the cavern
- a rotation and lateral sliding within the cavern
- a longitudinal sliding in the northbound tunnel, towards the break-in position

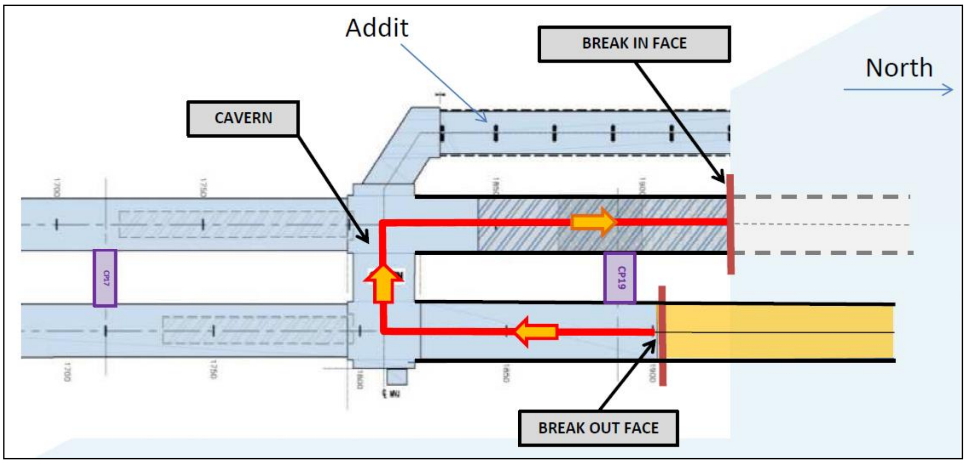


Figure 18: TBM transfer underground between the two TBM drives incl. U-turn in the Mid-Ventilation Junction Cavern

The main objectives identified for the TBM U-turn methodology were:

- Ensure safety to the workers and to the TBM equipment throughout the operation
- Minimize the extent of TBM dismantling and reassembly to keep the overall operation to a minimum duration, with a target of 3 months
- Early planning and preparation of the civil works for the TBM break-in of the second drive

To meet these objectives the following actions were taken by DHK:

- Engage the specialist company VSL Hong Kong to prepare and operate the TBM sliding operations
- Reuse and refurbish the TBM Turn Table from our Port of Miami Tunnel Project
- Rationalize the geometry of the Mid-Junction Ventilation Cavern to ease the construction of its permanent works, while allowing sufficient space for the TBM U-turn operation, which was validated by detailed BIM coordination, see Figure 19 below
- Launch an early detailed design with our Designer Atkins China Limited to develop a fit-for-purpose break-in thrust frame scheme, compatible with the faulted ground conditions identified during the excavation of the ventilation adit from the Mid-Portal, see Section 3.3 below

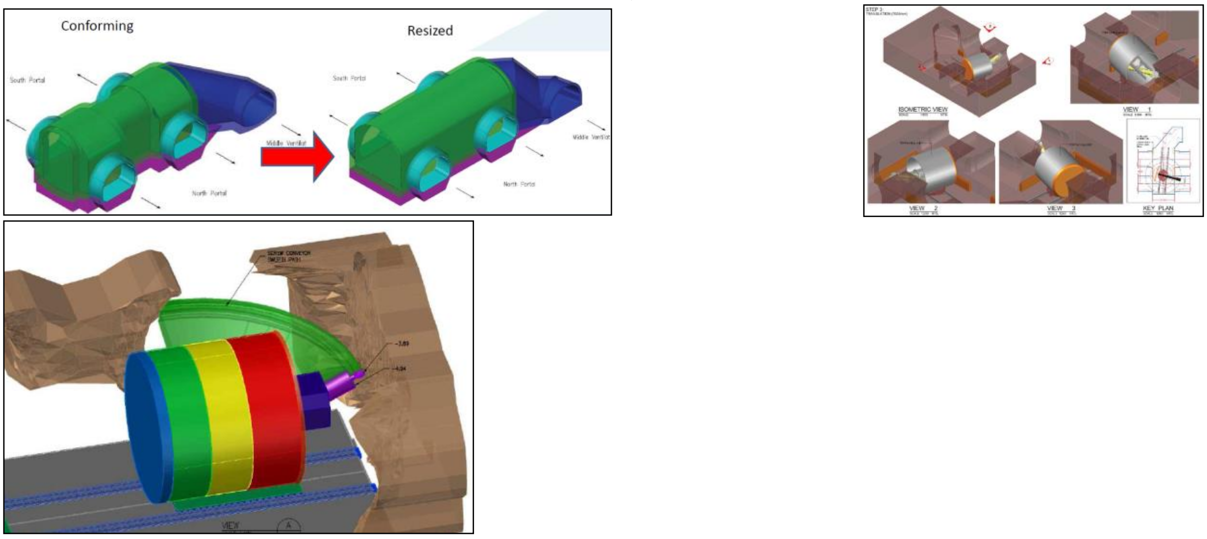


Figure 19: Mid-Junction Ventilation Cavern early space proofing and sizing study for rationalized permanent works construction and TBM U-turn operation

3.2 TBM U-turn Specific Methods, Technologies and Operation

The TBM U-turn operation took place in the 22 m span x 23.5 m high x 50 m long Mid-Ventilation Junction Cavern and adjacent tunnels shown on Plate 1 below.

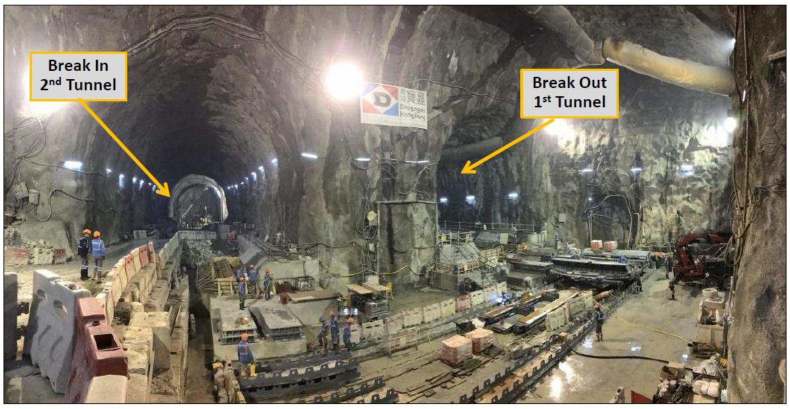


Plate 1: Overall view of TBM U-turn preparation in the Mid-Ventilation Junction Cavern and adjacent tunnels

For the sliding of the TBM elements, the heaviest of which was the TBM shield (2,500 tons), VSL Hong Kong implemented a solution using 2 units of 330 tons strand jacks providing a total pulling capacity of 660 tons. The TBM shield was placed on skid shoes with steel against brass interface, Figure 20.

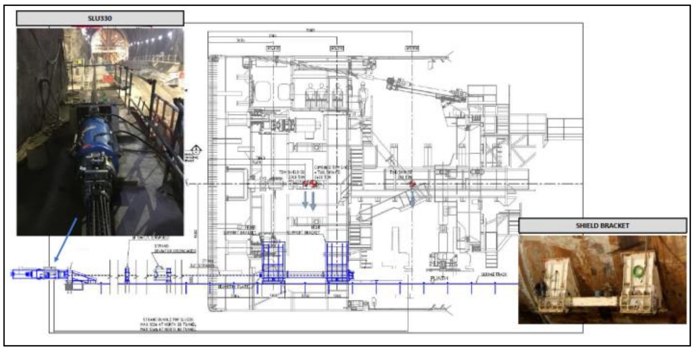
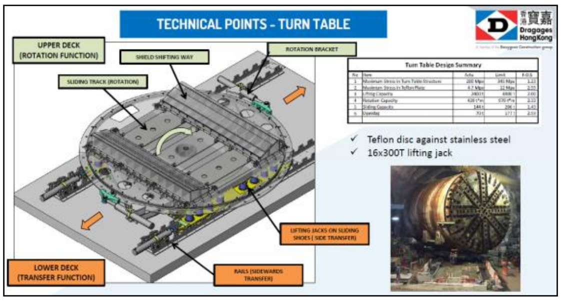


Figure 20: VSL Hong Kong Ltd jacking system used for TBM sliding

To rotate and translate the TBM in cavern an automated hydraulic Turn Table was used with a limit capacity of 4,800 tons. This Turn Table consisted of a lower and an upper deck separated by a Teflon pad to allow a low friction rotation. 16 units of 300 tons jacks were used to lift the Turn Table, while 2 units of 300 tons jacks were used for the translation system, and the last 2 jacks ensured a rotation capacity of 1000 tm.



- ✓ Teflon disc against stainless steel
- ✓ 16x300T lifting jack

Figure 21: Principles of the Turn Table used for the TBM U-turn and transfer operation

Plate 2 shows the transfer operation of the major TBM element including the cutter head, shield and screw. The same system was used for the transfer of all the TBM back up gantries which did not require to be dismantled.

Plate 2: TBM U-turn and transfer operations within the Mid-Ventilation Junction Cavern

3.3 Innovative TBM Break-in methodology in adverse ground conditions

Following the excavation of the mid-ventilation adit from the Mid-Portal, it was found that the TBM break-in originally planned was located in faulted ground. The risk was considered not acceptable and the TBM break-in location was shifted northwards just passed the geological feature, see Figure 22.

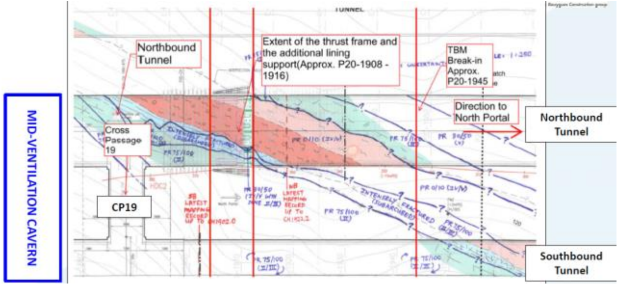


Figure 22 – Adverse geology in the TBM Break-in area of the 2nd northbound TBM drive

However, the TBM thrust frame behind had then to be designed for adverse ground conditions. In that context, based on 8 bar possible ground water pressure, we developed a hybrid thrust frame system made of:

a. A steel thrust frame connected to steel brackets embedded in a collar made of steel ribs and shotcrete above spring line / and supported by inclined steel struts to a reinforced concrete foundation at the bottom

b. A friction thrust frame, based on the mobilization by friction of the infill concrete between the tunnel segmental lining extrados over 8 rings and the arch ribs & shotcrete of the tunnel temporary support. T25 shear connectors were mounted at the segmental lining extrados to provide the required shear strength in the hatched areas indicated on the elevation of Figure 23 below.

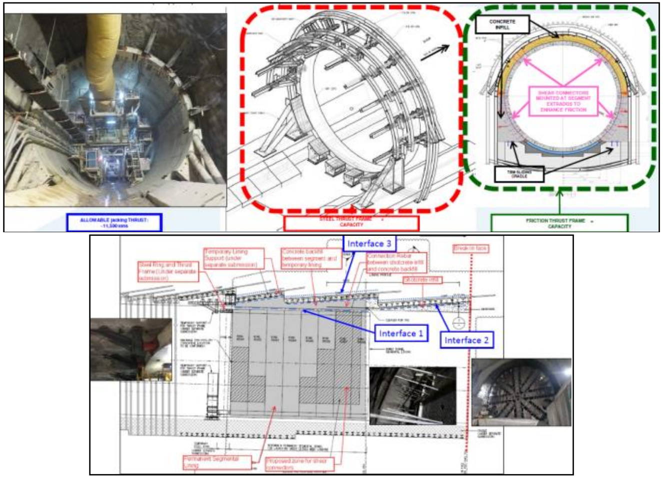


Figure 23 – Innovative hybrid thrust frame in adverse geology for the break-in of the 2nd TBM drive

3.4 Achievement

Thanks to a very detailed and early engineering of the Mid-Ventilation Junction Cavern spaceproofing, of the TBM U-turn operations, and of the TBM break-in system in the adverse ground conditions of the northbound tunnel, DHK managed to meet the objective of keeping the overall duration, between the break-out date of the first TBM southbound drive and the break-in date of the second TBM northbound drive, to 3 months only.

4 Conclusions

On the Liantang / Heung Yuen Wai Boundary Control Point Site Formation and Infrastructure Works – Contract 2, Dragages Hong Kong Limited proposed a series of advanced construction methodologies which benefited the Project:

- Use of a pilot 14.1 m diameter TBM tunnel in the tight horizontal curve from the North Portal, to reach the Mid-Ventilation Junction Cavern earlier and accelerate the progress of the excavation works
- Extend the TBM drives from 1,000 m to 2,400 m per tunnel to maximize the use of the EPB TBM
- Reduce the highest Project risk, by crossing the second valley and faulted ground area using the EPB TBM, instead of the mechanical or drill-and-blast technique of the conforming scheme
- Develop a safe methodology for the enlargement of the 315 m long pilot 14.1 m diameter TBM tunnel, off the critical path, and without any interruption of the logistics to the TBM operation ahead
- Implement very efficient TBM U-turn operation in the Mid-Ventilation Junction Cavern and preparation works for the innovative TBM break-in system developed for the adverse ground conditions of the northbound tunnel, which overall took 3 months only

These best-for-project technical solutions were implemented safely and resulted in an 8-month programme improvement.

5 Declarations

5.1 Acknowledgements

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5.2 Publisher’s Note

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