Ng, P.L., Polycarpe, S., Barrett, T.N.D.R., Roux, G. and Vallon, F. (2017) Development of a novel tunnel dismantling machine for the MTR West Island Line construction. HKIE Transactions, the Hong Kong Institution of Engineers, Vol. 24, No. 3, pp. 151-168

The Assessment Board selected this paper for the 2018 HKIE Geotechnical Paper Award, for its potential to advance local geotechnical practice and its quality of writing for the readership of practicing geotechnical engineers. It noted:

> The Tunnel Demolition Machine is a bold solution to a uniquely demanding project setting. Its success required precise ground and support modelling to guide the design of bespoke mechanical components and work cycles. The advanced technology applied would be of interest to practitioners. The paper instead takes readers through a perspective uncommon for project case papers, by providing a superb step-by-step record of how the project challenges were tackled. From it, one may appreciate the nature of innovation: persistent drive for better answers to issues, a wide and in-depth knowledge base to support creativity, and great attention to detail and rigorous preparation to ensure final success. The paper is well written with excellent figures and hence very readable.

"This is an Accepted Manuscript of an article published by Taylor & Francis Group in HKIE Transactions on 12/10/2017, available online: http://www.tandfonline.com/10.1080/1023697X.2017.1287012".

Development of the Novel Tunnel Dismantling Machine for the MTR West Island Line Construction

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Keywords:	Confinement, Hyperbaric intervention, Lining segment, Shotcrete, Tunnel dismantling machine, Tunnelling
Abstract:	The MTR West Island Line (WIL) Contract No. 703 Sheung Wan Station (SHW) to Sai Ying Pun Station (SYP) Tunnels is part of the extension of the existing MTR Island Line (ISL) of Hong Kong Island. The project involved the demolition and backfilling of 132 m of the existing Overrun Tunnel (ORT) through complex geology beneath a densely populated urban area, in order to enable subsequent excavation of the WIL Down-track (westbound) running tunnel by Tunnel Boring Machine (TBM). The innovation of a bespoke Tunnel Dismantling Machine (TDM) to tackle this challenge was adopted to minimise construction risks. A concrete bulkhead was built to separate the TDM works area from the Operational Railway. The TDM worked backwards from the operating railway interface inside ORT to remove each ring of lining segments under 2.8 bar compressed air pressure, spray shotcrete lining for temporary support and backfill of the remaining void left underground. The crew behind the demolition chamber of TDM remained at atmospheric pressure. Part of the backfilled tunnel was then re-excavated by slurry TBM to form the re-aligned WIL Down-track running tunnel. The TDM is unprecedented globally and it accomplished the works safely, successfully leading to the opening of WIL.

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Development of the Novel Tunnel Dismantling Machine for the MTR West Island Line Construction

Responses to Reviewer's Further Comments

P.L Ng*, S. Polycarpe, T.N.D.R. Barrett, G. Roux and F. Vallon

Reviewer 1:

Comment:
Please discuss the limitations of Plaxis 3D analysis, and the various factors that will contribute to the development of ground settlement. This will be useful to many young engineers who have no experience in soft ground tunnelling. If the authors can expand this part, this will be highly beneficial!

My previous experience with soft ground tunnelling in HK is a much higher ground settlement, and this issue must be addressed in more details for less experienced readers.

Response:
The Plaxis 3D analysis was conducted assuming linearly elastic-perfectly plastic behaviour of the geological strata, which were modelled as Mohr-Coulomb materials. However, as detailed later in the paper, there were free air interventions in the TDM work cycling. The dissipation of compressed air was a process where the voids in soil once filled with compressed air were re-occupied by water. Such flow of water would degrade the soil skeleton and aggravate the deformations. Due to limitations of the materials modelling, the above effects could not be taken into account in the Plaxis 3D analysis. Hence, the ground settlement and face loss would be underestimated. The analytical value of ground settlement was exceeded during construction. Nevertheless, no unacceptable movement of the existing buildings and structures was induced. The above has been incorporated in the revised paper. In addition, general revisions have been made in the paper for improvement in English. All revisions have been highlighted in the re-submitted electronic file of paper.

- End -

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Development of the Novel Tunnel Dismantling Machine for the MTR West Island Line Construction

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Abstract: The MTR West Island Line (WIL) Contract No. 703 Sheung Wan Station (SHW) to Sai Ying Pun Station (SYP) Tunnels is part of the extension of the existing MTR Island Line (ISL) of Hong Kong Island. The project involved the demolition and backfilling of 132 m of the existing Overrun Tunnel (ORT) through complex geology beneath a densely populated urban area, in order to enable subsequent excavation of the WIL Down-track (westbound) running tunnel by Tunnel Boring Machine (TBM). The innovation of a bespoke Tunnel Dismantling Machine (TDM) to tackle this challenge was adopted to minimise construction risks. A concrete bulkhead was built to separate the TDM works area from the Operational Railway. The TDM worked backwards from the operating railway interface inside the ORT to remove each ring of lining segments under 2.8 bar compressed air pressure, placed a sprayed concrete lining for temporary support and backfill of the remaining void left underground. The crew behind the demolition chamber of TDM remained at atmospheric pressure. Part of the backfilled tunnel was then re-excavated by slurry TBM to form the re-aligned WIL Down-track running tunnel. The TDM is unprecedented globally and it accomplished the works safely, successfully leading to the opening of WIL. This paper explicates the TDM development with the design and construction aspects of the tunnel dismantling works.

Keywords: Confinement; Hyperbaric intervention; Lining segment; Shotcrete; Tunnel dismantling machine; Tunnelling.

1. Introduction

The MTR West Island Line (WIL) Project extends the existing Island Line (ISL) service along the northern shore of Hong Kong Island from Sheung Wan Station (SHW) to Kennedy Town (KET) via Sai Ying Pun (SYP) and HKU Stations, adding approximately 3.3 km of underground route length of the ISL and three new stations. Figure 1 shows the layout plan of WIL. The SHW to SYP Tunnels belong to the scope of WIL Contract No. 703 (WIL703), which comprises the Up-track (eastbound) running tunnel and the Down-track (westbound) running tunnel excavated by both Tunnel Boring Machine (TBM) and Drill-and-Blast methods (Baribault et al. 2012; Tsang et al. 2012), construction of access tunnels and shafts at King George V Memorial Park and Sai Woo Lane, artificial ground freezing gallery at existing SHW Crossover Box (COB) near Western Market to remove pre-existing obstruction prior to TBM tunneling (Polycarpe et al., 2012; Wong et al. 2012), construction of SYP Station Entrances A1/A2 structure, and other associated works. Figure 2 shows the general layout of WIL703 project.

Concerning the connection of new tunnels to the existing infrastructure, the existing Sheung Wan Overrun Tunnel (ORT), which stretches about 500 m from SHW COB to Ko Shing Street, was designed with a planned future extension in mind. However, the urban reclamation development originally planned for the northern coastline of the Western District was not undertaken. Through public consultation and design review, the WIL running tunnels were realigned further inland, i.e. towards the south, to better serve the development catchment of the Western District. Thus the end portion of the existing ORT planned for the extension no longer suited the revised alignment with the new westbound running tunnel connecting halfway along the existing ORT. Visualisation of the 3-dimensional geometry of the connection of WIL Down-track running tunnel to the existing ORT is illustrated in Figure 3. A section of the ORT circa 132 m length conflicted with the new Down-track running tunnel and needed to be demolished prior to the new tunnel construction.

The existing ORT served the function of allowing trains on the Down-track to go beyond the COB and come back in the reverse direction on the Up-track. An extended length of ORT was provided for such that any train that breaks down can be shunted by the following train into the extended length acting as a refuge siding. This provision is of key importance in maintaining the MTR railway operations in case of train breakdown. During demolition of the ORT and construction of the tunnel connection, the refuge siding section of the ORT and the adjoining ventilation shaft at Ko Shing Street (refer to Figure 2 for the locations on plan) were isolated from the operational railway. The period for this degraded provisioning to the operating system by a shortened, or degraded, refuge siding was limited to twelve months before the replacement refuge siding in the new Up-track running tunnel is operational.

The ORT is an undrained tunnel with external diameter of 5.8 m and is lined with rings made of precast reinforced concrete or spheroidal graphite iron (SGI) segments. The precast concrete lining is 1.0 m wide and 0.25 m thick, whereas the SGI lining is 1.0 m wide and 0.15 m thick. The internal diameter of the ORT is 5.3 m at the precast concrete lining sections and 5.5 m at the SGI lining sections. A photograph of the ORT showing both types of lining is given in Figure 4. The 132 m length section of ORT demolished 125 precast concrete rings and 7 steel rings. The ORT is curved on plan and the minimum radius of curvature is approximately 600 m, and it has a 0.5% gradient sloping down from SHW side to the Ko Shing Street ventilation shaft.

The geology is variable and complex, with the majority of the ORT section embedded in Completely Decomposed Granite (CDG) with corestones, and overlain by alluvium and marine deposits including old sea walls. The tunnel invert at two ends of the ORT section is close to or slightly below the level of fresh granite bedrock, whose rockhead levels vary greatly. The maximum groundwater head above the tunnel invert level is 27 m. Figure 5 illustrates the geology along the longitudinal section of ORT. The ORT and the new Down-track running tunnel are situated underneath dense urban areas with limited clearances to the existing building foundation piles, the closest being circa 400 mm.

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The section of ORT to be demolished was sealed from the operational part of railway ORT by constructing a 6 m long mass concrete bulkhead. After the bulkhead was in place, the existing ORT lining was cored through and grouted to fill any voids and high-pressure grouting was used to reduce water ingress through the rock interface. The ORT segment joints were caulked to improve the seal between the TDM and the lining, the SGI lining pans between ribs were filled with mortar, the existing MTR rails and track bed were removed to allow site installations of the TDM to commence. The grouting limited the potential air leakage into the soil as well as to strengthen specific areas of the ground where thrust loads would be dissipated through thrust rings (nevertheless for conservatism in design, the strengthening effect of the ground due to grouting was not utilised to resist the thrust load).

The demolition of existing ORT was performed by a bespoke Tunnel Demolition Machine (TDM) which was innovated for the WIL703 project. Though the TDM is unprecedented worldwide, meticulous planning, risk management, design and site implementation allowed the works to be accomplished safely and without delay to the opening of WIL. This paper presents a detailed account of the development of this novel machine and describes the design and construction aspects of the tunnel dismantling works.

2. Conceptual Development

As the demolition of ORT presents a peculiar challenge to the WIL construction, a number of construction schemes had been formulated throughout different stages of the project. In the preliminary design stage of the project, it was envisaged that the ORT needed backfilling first, and followed by simultaneous excavation of the future westbound tunnel and removal of the existing ORT lining using a Greathead shield (GHS), an open face tunnelling machine that was used in the 1980s during the construction of MTR ISL. In the tendering stage of WIL703, Dragages-Maeda-BSG Joint Venture (DMBJV) (subsequently the Main Contractor of WIL703) reviewed the methodology to remove the existing ORT lining. It was opined that the GHS scheme had the following drawbacks: (1) the face stability of GHS would be difficult to manage and there might be risk of major groundwater inflow; (2) more serious health and safety concerns due to frequent compressed air interventions would be required; (3) high risk of significant delays due to heavy reliance on manual operations; and (4) not suitable for rock geology which was anticipated when approaching the tunnel connection.

Besides, the use of an Air Plenum Shield Machine was considered and it was not favoured in view of the following drawbacks: (1) difficult to maintain the face stability;

(2) significant risk of machine and screw conveyor damage by lining rebars; (3) possible delays due to more frequent machine repair; (4) health and safety risks associated with numerous compressed air interventions to repair the cutter tools; and (5) not suitable for rock geology.

As a result, DMBJV proposed to dismantle the existing lining then backfill the ORT by a bespoke Tunnel Dismantling Machine (TDM), before the newly aligned westbound tunnel is excavated by a slurry mix-shield TBM (slurry TBM was employed in view of geology along the running tunnels (Tsang et al. 2012)). Figure 6 illustrates the conceptual view of the TDM. During the tunnel demolition process, the TDM incrementally moves backwards metre by metre (towards the west direction) from inside the ORT, i.e. from the bulkhead towards the Ko Shing Street ventilation shaft. The TDM removes the lining one ring at a time using a demolition arm with a high-power breaker and grabbing claws from within the demolition chamber under 2.8 bar air pressure, these demolished segments are removed via an airlock for removal to surface.

The demolition arm is also equipped with a shotcrete nozzle and applies a shotcrete lining as temporary support to the exposed ground of the ORT, the remaining void is then backfilled. With the exception of deploying specially-trained personnel for conducting geological inspections and machinery maintenance in hyperbaric condition, the TDM operator and all support personnel are remained behind the TDM front shield under atmospheric pressure. Subsequent to the ORT demolition, the backfilled ORT was re-excavated by a slurry TBM to form the newly aligned Down-track running tunnel. A brief account of the principle development of the TDM was given by Vallon et al. (2011, 2013).

It is notable that with the functions of segment lining removal, temporary support concrete spraying, and tunnel void backfilling combined into a single TDM, the work activities could be readily implemented in a cyclic manner, such that good face stability at every stage of work could be ensured. Thus, the TDM scheme could best mitigate construction risks as well as safeguard the health of the workforce under atmospheric condition and protected against the compressed air environment and the exposed geological risks. This novel scheme was fully supported by MTR Corporation Limited.

3. Details of the TDM

With the input from MTR Corporation Limited, DMBJV collaborated with CSM Bessac to design and develop the TDM, which demanded dedicated effort and innovative thinking to overcome the complex technical challenges. For example, the TBM confinement concept had to be re-established and re-engineered for application to the TDM due to the specific configuration and functionality of this novel machine; the works cycle had to be tailored to consider the specific conditions and constraints of the site. The TDM is composed of different functional components as detailed in the following with the aid of an anatomic view in Figure 7. Fabrication of the TDM was undertaken at the facilities of CSM Bessac in Toulouse, France.

The articulated demolition arm is multifunctional and it utilises:

1. a retractable hydraulic breaker for demolition of the existing segments;
2. grabbing claws for manipulating segments for removal and transferral to the material lock;
3. a scraper plate for cleaning the invert;
4. shotcrete nozzle and umbilicals for concrete spraying; and
5. a device for verifying the thickness of newly formed shotcrete lining.

The arm comprises two articulated modules on a horizontal turret, and is able to operate radially through a full range of 360 degrees. It is worthwhile to note that the design of this heavy duty and sophisticated demolition arm with many movable parts presented enormous engineering challenges in its own right. Robust protection systems for the arm without interfering its functionality and movability were a requisite as was the trial testing.

The TDM is equipped with two man locks and a material lock. The man locks are provided to compress and decompress the workers undergoing hyperbaric interventions in the demolition chamber at the front of TDM. The durations of compression before hyperbaric work and decompression after hyperbaric work were determined according to the project decompression tables approved by the Labour Department of Hong Kong for compressed air work. The tables were based on the

French Ministry of Labour Tables (Direction des Journaux Officiels 1992), which are commonly referred to as French Decompression Tables. The material lock allows loading and transfer of the demolished lining segments and debris to free air for removal. Due to the limited width of the material lock, the demolished segments needed to be rotated 90 degrees to enter into the material lock with its shortest side (i.e. 1.0 m width of segment). The lock is fitted with a transfer platform that receives interchangeable segment skips.

The ring being demolished is temporarily propped in the crown by six telescopic arms which support the upper half of ring in place once the key is removed to avoid uncontrolled dislocation~~removal~~. The upper part of the front shield is also fitted with telescopic crown protection plates for worker protection from falling material. In the event of equipment breakdown or mechanical incident, safe access to the demolition arm is maintained and protected by the plates. The plates also offer protection to workers when they cleaned the spraying nozzle after shotcreting under hyperbaric condition.

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The shields of TDM comprise the front shield, central shield, and rear shield. The shields have an external diameter of 5.1 m and their total length in longitudinal direction is approximately 6.8 m. The shields protect the TDM components, contain the compressed air, and provide articulations (between the front and central shields and between the central and rear shields) so as to cater for the curvature of ORT.

The tail skin of rear shield is separated from the body of TDM by an articulation joint and seal, enabling all-round radial movement of 20 mm so as to allow optimal centering of the TDM inside the tunnel. This facilitates adjustment of the TDM position to accommodate the curvature of the ORT as well as the initial deviations of the ORT lining cross-section from a perfect circle. While allowing the radial movement, the tail skin has to be air-tight to maintain the compressed air in the demolition chamber from atmosphere pressure in the operating area. To achieve effective sealing while giving flexibility to suit the tunnel geometry, the tail skin seal was formed by three sets of wire brushes with grease injection forming two sealant chambers against the segment intrados, as illustrated in Figure 8. Hence it was imperative to fill all the ORT segment joints and bolt pockets prior to dismantling to prevent leakage around the seals. This is in contrast to the provision of rows of brushes for sealing a TBM, where the brushes are sealed against the extrados of the lining segments.

The compressed air pressure must be maintained to provide the necessary confinement for the TDM. The compressed air was generated by two breathable air compressors (one active and one stand-by) each of capacity 500 litre/second at 2.8 bar. Both units were installed in the existing Ko Shing Street ventilation shaft and were connected to an emergency generator in case of power supply failure. The compressed air system was design to withstand a maximum air loss of 500 litre/second. Nonetheless, the actual air loss rates experienced during dismantling were far less than the limit and no problem was encountered during the control of the compressed air pressure.

4. Testing and Validation

In order to validate the functionality of various elements of the TDM, a number of reduced scale and full scale tests, including mock-up trials, were undertaken in Toulouse, Paris and Hong Kong. The tests included testing of the demolition arm hydraulic breaker, segment removal tests, air tightness tests of the external brushes sealing in compressed air, 3 m diameter bench test, shotcreting trials in compressed air inside a 3 m diameter pressure chamber; trial installation and assembly of TDM and trial operation of TDM inside a 15 m long full scale mock-up tunnel.

Figure 9 depicts the testing of the demolition arm during segment handling. As the demolition arm was complex and versatile, it was thoroughly tested with purposely-made precast lining segments replicating the existing ORT segments. The segment concrete breaking, removal of segment from its constructed position, and handling of segment including moving and rotating by grabbing were fully validated by testing regime. The spraying of shotcrete from the nozzle installed at the demolition arm was also fully tested. Considering the need to operate the demolition arm with 360 degree freedom, the above tests were arranged to validate the functioning of demolition arm through all configurations.

Figure 10 depicts the validation test of the tail skin wire brushes seal arrangement. The tail skin seal comprising of three sets of wire brushes with grease injected between was placed concentrically as well as eccentrically into a prefabricated steel ring constructed to the worst case as-built tunnel geometry of the ORT. Compressed air was applied to the annular space between the ring and tail skin at the predefined pressures up to the maximum design pressure. After switching off the compressed air supply, a manometer was employed to monitor any drop in pressure, initially the pressure drop was found excessive but subsequent to redesigning and reinstalling the brushes, the test was re-run and the pressure drop was found to be negligible. The final result proved that the air loss through the tail skin was inconsequential compared to the replenishing rate of the breathable air compressor and as such was a success, and it also highlighted the importance of such tests. A circular rubber seal and rear adjustable sealing plates were also installed as a backup in case the seal was lost.

Figure 11 depicts the bespoke pressure chamber for conducting shotcreting trials in compressed air. The chamber had a diameter of 3 m, which was approximately half the scale of the ORT. The compressed air applied was at a maximum pressure of 3.15 bar, which adequately simulated the concrete spraying environment in the demolition chamber. Through extensive shotcrete trials both in Paris and Hong Kong, it was proven that shotcrete could be sprayed accurately and build-up to the required thickness in the compressed air environment up to 3.15 bar and adhere to surfaces around the 360 degree range where panels were placed in the chamber at differing angles from the horizontal to simulate such.

The trials also provided useful data for adjusting the shotcrete mix designs such that its workability regime for spraying, rate of strength development under compressed air environment, strength at different ages, and robustness of performance against variations in operation parameters could satisfy all requirements. The in-situ strength of shotcrete was measured with core samples taken from the shotcrete panels. It should be noted that the strength versus time relationship is a key performance attribute, based on which the thickness and the time to permit loading on the temporary shotcrete lining support were determined in the detailed design. To render the test results applicable to local concrete ingredient materials, the shotcrete trials were conducted in Hong Kong.

The pressure chamber was conforming to statutory requirements of the Boilers and Pressure Vessels Ordinance of the Laws of Hong Kong.

Figure 12 depicts the mock-up tunnel for testing the TDM. Prior to the mock-up trial in full scale, trial assembly and disassembly of the TDM in components and in full had been conducted. The mock-up trial enabled revealing of potential problems in every element of work, so that fine-tuning of the machinery could be made for improved work process.

5. Analysis and Design

The demolition of ORT was simulated by 3-dimensional finite element modelling by the software Plaxis 3D. Figure 13 depicts the finite element analysis. The soil and rock were modelled as Mohr-Coulomb materials, and their properties ~~of soil and rock~~ were established from the ground investigation results. The earth pressure, building loads, surcharges and hydrostatic pressure were considered. During the tunnel demolition work, the new Up-track (eastbound) running tunnel was already excavated. Therefore, both the effects of presence of Up-track running tunnel on ORT demolition as well as the effects of ORT demolition on the Up-track running tunnel needed to be analysed. In the finite element modelling, the presence of ORT, Up-track running tunnel, as well as the construction sequence were simulated. The analysis results had verified that the proposed compressed air pressure of 2.8 bar was adequate to ensure the face and sides stabilities of the unsupported excavation.

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The ground settlement and face loss were evaluated. According to the analysis results, the maximum ground settlement was 2.4 mm, and the maximum face loss was 0.4%. No significant effect on the existing buildings and structures would result from these movements. It should be noted that the Plaxis 3D analysis was conducted assuming linearly elastic-perfectly plastic behaviour of the geological strata. However, as detailed later in the paper, there were free air interventions in the TDM work cycling. The dissipation of compressed air was a process where the voids in soil once filled with compressed air were re-occupied by water. Such flow of water would degrade the soil skeleton and aggravate the deformations. Due to limitations of the materials modelling, the above effects could not be taken into account in the Plaxis 3D analysis. Hence, the

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ground settlement and face loss would be underestimated. The analytical value of ground settlement was exceeded during construction. Nevertheless, no unacceptable movement of the existing buildings and structures was induced.

The minimum thickness of temporary shotcrete lining was established by the finite element analysis. Structural actions of the temporary shotcrete lining were evaluated from the Plaxis 3D computation results. Early strengths of shotcrete were obtained from the shotcreting tests for deriving the shotcrete strength development curve. The axial, flexural and shear capacities of the shotcrete lining were checked based on the M-N (bending moment-axial force) interaction envelopes at different ages. The design checking confirmed that shotcrete lining of 300 mm thickness would be sufficient to replace the existing lining in supporting the ground. In conjunction with the given thickness, the time to permit loading onto the shotcrete lining was determined based on the strength of shotcrete achieved, which was a key design criterion requiring verification during construction.

Sensitivity analysis was conducted with the variation of compressed air pressure, shotcrete strength, shotcrete thickness and length of unlined section. Optimisation of the production cycle was carried out based on the sensitivity analysis results. The assessment of temporary shotcrete lining for different lengths of unlined section is illustrated in Figure 14. By verifying the loading on the preceding installed temporary shotcrete lining for different lengths of unlined sections, the viability of 1-ring cycle (dismantling 1 segment ring followed by shotcreting) and 2-ring cycle (dismantling 2 segment rings followed by shotcreting) was established.

It should be noted that for the first four rings, where the new Down-track running tunnel connects with the existing ORT, an over-excavation of 600 to 900 mm was required for the arrival of the TBM. This enlargement was constructed to allow room for dismantling the TBM cutterhead as well as for construction of the in-situ permanent reinforced concrete tunnel lining at the new TBM tunnel to ORT connection under atmospheric pressure. The shotcrete lining of the over-excavated portion will provide support against the earth pressure during cutterhead dismantling and permanent lining construction. Such over-excavation and shotcrete lining were included in the

Plaxis 3D finite element modelling and duly checked in the detailed design to be safe and adequate.

A comprehensive instrumentation and monitoring (I&M) plan was included in the design and as part of the WIL703 project I&M plan. At ground surface, within the monitoring zone, the ground settlement and groundwater drawdown were respectively measured by ground settlement markers and piezometers and recorded systematically as per the I&M plan. Building movements were monitored and recorded by the Automatic Deformation Monitoring System (ADMS) (Tse and Luk 2011), which comprised strain gauges and prisms. Underground the operational railway was also monitored using ADMS to record and highlight movements, whereas the new Up-track running tunnel and the section of ORT to be demolished were manually surveyed using prism convergence arrays along the tunnels. Alert-action-alarm (AAA) values were defined in the I&M plan with corresponding contingency measures to be undertaken should the AAA levels be reached.

6. Site Installations

6.1 Ground surface and ventilation building

The surface site area occupies a curved-shape junction in Ko Shing Street, a 45 m long by 4.5 m wide working area formed by closing a section of traffic lane in Des Voeux Road West, and the existing disused ISL ventilation building (Figure 15). The site faced extreme constraints in terms of noise limitation, space and access. Apart from the ground surface, the ventilation shaft, connection adit and section of ORT (approximately 250 m long) behind the bulkhead were utilised for site installations and logistics. In view of the limited construction area, the site installations were set up at the surface, at various levels in the ventilation building and shaft, and along the ORT.

The site installations at the ground surface included a water treatment plant, an electric switch container, 1000 kVA mini sub, an emergency generator with cooling tower situated above, and a concrete pump with emergency compressor situated above. In Ko Shing Street, a 10 ton lifting capacity monorail crane was erected to serve the shaft access opening (Figure 15). The disused ventilation building was used to set up the temporary ventilation comprising a 55 kW fan for the inlet and a 30 kW fan for the outlet, both with silencers. For noise reduction purpose, the shaft was covered by noise attenuating panels and the access opening of ventilation building was protected by double noise attenuating doors. The noise cover could reduce the audible noise by as much as 51 dB(A) (Ho et al. 2012), to achieve this the cover and doors had to be properly closed at night.

6.2 Ventilation shaft

The ventilation shaft was 30 m deep with diameter between 7.4 m and 6.4 m. Figure 16 illustrates the site installations in the ventilation shaft. A man-lift was installed to allow easy access in/out 24 hours a day and a rigid vertical duct was installed to supply fresh air to ventilate the tunnel. Additional exhaust fans were installed to improve the ventilation to mitigate the heat generated by the curing shotcrete and the underground plant, especially as the works were undertaken during the hot summer months. The supply of compressed air was set up in the shaft, including 2 nos. 10 bar industrial air compressors (for shotcreting) plus air receivers and 2 nos. 2.8 bar breathable air compressors (for confinement) with a power pack installed at the shaft base. Existing utilities and the structure of the shaft limited the clear opening used as a lifting window which formed a small non-rectangular shape as shown in Figure 16, the TDM parts for assembly in the ORT were designed with the opening size in mind.

6.3 Connection adit and ORT

The underground site installations were arranged to allow 24-hour operation of tunnel dismantling and backfilling. The length along the ORT available for major site installations without obstructing the service train was circa 50 m, where the site installations are presented in Figure 17. There was a short connection adit of approximately 7.4 m in length with cross-section of 3.9 m (width) by 3.0 m (height) between the bottom of ventilation shaft and the ORT. To facilitate transportation of materials to and from the ORT, rails were installed along the ORT and the adit for running flat cars. In the adit, a 3 ton winch was used to transport the flat car; in the ORT, a service train comprised of a 10 ton Clayton locomotive with flat cars was utilised. Loading and unloading of the flat cars and service train as well as general lifting were facilitated by a 3.2 ton capacity stationary jib crane and a 10 ton capacity Fassi crane mounted on a 6 m long flat car in the ORT.

At the head wall of the ORT, a concrete mixing area comprising two agitator tanks of 7 m^3 and 9 m^3 installed above the concrete pump was set up. The concrete was pumped via the concrete pipeline to the shotcrete machine behind the TDM. Storage platforms of circa 20 m total length were installed along the ORT to provide space for temporary storage of segments dismantled during night shift whilst the noise cover on the top of ventilation shaft was closed. Working at height in the ORT was assisted by a cherry picker.

To supply fresh air and improve the ventilation, an air duct was installed from the shaft along the connection adit and ORT to the TDM, and ventilation fans were employed to provide air circulation. Temporary services for tunnel dismantling including water supply and waste water discharge pipes, compressed air pipes, concrete supply pipes, power, task and emergency lighting cables, and data cables were installed on temporary brackets along the ORT wall. A temporary walkway was also installed along the wall so as to separate the pedestrian access from the service train passage.

7. Tunnel Dismantling Operations

7.1 Ground treatment

Prior to launching the TDM, the ground mass around the ORT had been treated by grouting to minimise the loss of compressed air. Moreover, the ORT segment joints, bolt pockets and SGI lining pans were filled by mortar to avoid compressed air leakage. These works also served the purpose of minimising water ingress into the ORT. It was noted that after lunching the TDM, additional grouting was performed as necessitated by local variations of the geology.

7.2 TDM assembly

The TDM was delivered on site and lifted down to tunnel level by the monorail crane in parts not exceeding 10 ton and with dimensions fitting with the lifting window of the shaft. With the experience gained in the trial assembly of the TDM in CSM Bessac's facilities, the assembly on site was smoothly completed in 55 days with the use of the Fassi crane mounted on flat car. Figure 18 depicts photographs of the TDM assembly process. The completion of assembly was immediately followed by testing and commissioning of the control system, initial checking of thrust structures (which will be further explained below), staged hydrostatic tests (hydrostatic pressure instead of compressed air pressure was exerted for more stable pressure increment and decrement), as well as rechecking of the thrust structures at pressure increments and after unloading.

7.3 Segment dismantling and shotcrete lining

The TDM dismantled the lining segments using the demolition arm. Prior to dismantling, the telescopic arms were extended to prop the leading edge of the segment ring being dismantled to secure the upper half of the ring from sudden falling, and gripper pads were extended from the body of the TDM to secure it in position. Existing segment bolts were destroyed with the hydraulic breaker. Demolished segments were transferred by grabbing to the material lock at the invert for removal. When a segment ring was demolished, temporary shotcrete lining was constructed using the spraying nozzle. During shotcreting, the concrete was delivered from the concrete mixing area at the far end of the ORT by pumping along the concrete pipeline. The demolition and shotcreting operations were carried out under 2.8 bar compressed air pressure. Upon completion of the shotcreting lining, the thickness of lining was spot checked with the automatic surveying device installed in the TDM. The actual thickness of shotcrete lining was always not less than the design requirement of 300 mm. Figure 19 shows the photographs of segment dismantling and shotcreting.

The mix design of the temporary shotcrete lining had been established and validated from shotcrete tests and trial mixing. The properties of shotcrete for temporary lining met the expectations and satisfied all the requirements. The only ~~E~~exception was due to the high temperature of the ORT work site, there was potentially rapid loss in workability, and the deterioration in consistency might cause rebound and induce weak planes when the shotcrete lining built up its thickness. To help control the high temperature and remove the concern of rebound weak planes, part of the mixing water was replaced with ice and additional retarder was dosed into the mix.

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For the first 4 rings, the over-excavation progressed smoothly and for conservatism, extra thickness of temporary shotcrete lining (400 mm instead of 300 mm) was constructed before backfilling. For the last 7 rings of SGI segments, they were demolished by breaking with the hydraulic breaker of the demolition arm due to their brittle nature. The last few rings only partially encroached into the TBM alignment and as such partial demolition of the encroaching segments was implemented.

7.4 Backfilling

Initially there were two concepts for backfilling the void, the first was to demolish the lining for one week and then backfill using staged formworks under free air, the second option was to demolish several rings and then use the shotcrete nozzle for backfilling. After various trials and site experimentation it was found that using the shotcreting nozzle was the most efficient way to fill the void. This will be further discussed in Section 7.6.

The backfill material was a low-strength PFA (pulverized fuel ash)-cement mix with 28-day compressive strength of not less than 1.5 MPa. The mix contained PFA as the major ingredient and cement was used as a binding additive in order to ensure minimal heat during curing. The low cement content also reduced the degradation of the bentonite slurry used to support the excavation of the future TBM tunnel. Since PFA is a waste product from power stations, the mix is very environmentally friendly. The selection of compression strength criterion was such that the backfill material is not too weak to cause additional ground settlement after backfilling, and not too strong to invoke unnecessary cement consumption. Trial mixing was conducted prior to the launching of TDM to establish the mix proportions of the backfill material.

7.5 Thrust reaction structure system

The TDM retreats along the ORT as the tunnel is demolished and backfilled. The 2.8 bar compressed air pressure of the TDM operation creates a thrust force trying to push the TDM backward in the order of 700 ton. This force must be counteracted by a thrust reaction structure system to ensure the stability of the TDM. The thrust reaction structure system, which consisted of three reinforced concrete thrust reaction rings and a steel thrust reaction frame as shown in Figure 20, will be explained below.

The 132 m long section of ORT was divided into 3 equal sub-sections of 44 m and a reinforced concrete thrust ring had been constructed at the end of each sub-section. Between the concrete thrust ring and the TDM, a steel thrust frame was installed along the sub-section to transmit the backward force via the concrete thrust ring to the surrounding treated ground. The steel thrust frame consists of steel struts coaxial with the 8nos. perimeter hydraulic thrust cylinders of the TDM, and steel arches restraining the struts at every 3 m interval (corresponding to the stoke length of TDM thrust cylinders). The length of struts was approximately 3 m but supplied in two sets, with difference of 20 mm between the two sets (coloured in blue and red respectively for easy distinguishing) so as to accommodate the curvature of the existing ORT. To economise the fabrication quantities of steel arch and strut members, the steel arches and struts were disassembled with the Fassi crane for recycling to the subsequent sub-section as the TDM retreats every 3 m. The division of sub-sections ensured the stability of steel thrust frame by limiting its length thus limiting its misalignment which might cause buckling, moreover this reduced the quantities of steel arches and strut members required as for each sub-section the same thrust reaction frame was re-used.

As the steel thrust frame was composed of steel struts in circa 3 m lengths connected end to end, the overall stability of frame was a key consideration albeit the restraint provided by its steel arches, because major misalignment could cause buckling and failure. Therefore, the installation of steel thrust frame was subject to a tight tolerance prior to loading. Moreover, throughout the TDM operation the stability of the steel thrust frame, especially the alignment of struts, was closely inspected on a daily basis and re-checked immediately after any change in configuration prior to loading (e.g. shortening of the frame when the TDM retreated, or depressurisation followed by re-pressurisation of the TDM). The daily inspection included checking the force readings from each TDM hydraulic thrust cylinder and the compressed air pressure to ensure the forces among the thrust cylinders and the compressed air pressure varied within respective acceptable ranges. Furthermore, to eliminate eccentric loading on the thrust frame when the TDM is moving backward, an anti-rotation device was installed to prevent the TDM roll. It was found that the pitch remained stable.

When the tunnel dismantling for one sub-section was completed, the concrete thrust ring needed to be removed for the TDM to move backward. At this juncture, the TDM was stopped after finishing the last cycle of temporary shotcrete lining and backfilling. Then the TDM was depressurised, i.e. the pressure in demolition chamber dropped to atmospheric pressure, for up to 1 week during the concrete thrust ring demolition. Figure 21 shows a photograph of demolition chamber during an atmospheric stop. The decompression of TDM was a critical activity that must strictly follow a detailed staged decompression plan to ensure no undue ground deformation and surface settlement.

7.6 Work cycling

The initially planned work cycle involved shotcreting the exposed ground after dismantling each ring with weekly backfilling of the tunnel at atmospheric pressure. It was thought that this weekly cycle scheduling would provide the best production rate. Mobilisation of backfilling at a weekly frequency with the large volume of backfill placed using a concrete pump (with 40 m^3/hour rate) rather than a shotcrete pump (with 10 m^3/hour rate) would save time. However, this scheduling had certain demerits. The setting up of formworks took time, and it had to be close to the excavation area impeding the next demolition cycle or had to be outside the reach of the crown protection plates. Furthermore, the weekly cycle prolonged the standing time of the temporary shotcrete lining (the longest is close to 7 days for the first ring in the cycle). After reviewing the potential risks, an alternative work cycle was developed.

With the considerations to maintain the confinement by compressed air and to minimise hyperbaric works as much as possible, it was decided to use the option to backfill the tunnel under compressed air, on a daily basis with the use of shotcrete. The shortened standing time of tunnel void before backfilling also helped to reduce the risk of ground settlement. The weekly cycle was revised such that scheduled maintenance works would be carried out in weekends in the demolition chamber at atmospheric pressure. Before depressurising, all shotcrete sprayed during the cycle must be confirmed by tests to have at least 15 MPa compressive strength and 300 mm minimum thickness. Design checking was performed to validate both sequences of dismantling 1 ring followed by shotcreting and backfilling (1-ring cycle) and dismantling 2 consecutive rings followed by shotcreting and backfilling (2-ring cycle). The latter sequence was achievable on site in 24-hour cycles (dismantling in night shift and completing the backfilling within the following day shift), thus it was adopted and the overall production rate met the original programme.

7.7 Controlling the heat

One major problem encountered during the ORT dismantling operation was the high temperature (accompanied by high humidity) of the working environment. The heat was due to multiple causes, including the air compression process, heat generated by the shotcrete and backfill, heat generated by plant, and the high ambient temperature in the Hong Kong summer. In particular, the thermal energy accumulated in front of the TDM could not be effectively removed by ventilation alone. In order to mitigate this problem, a number of measures were implemented, including installation of breathing air and industrial air driers and coolers, deployment of extra ventilation fans, adjustment of shotcrete mix and replacing mixing water with ice, inundating the demolition chamber, reducing the number and duration of hyperbaric interventions, prolonging decompression and resting time after hyperbaric interventions, providing ice jackets for hyperbaric workers (Figure 22), supplying cool water and energy drink to the workforce, and organising training for workers to recognise heat stroke symptoms and precautions.

8. Conclusions

To tackle the uncommon problem of constructing a new re-aligned MTR West Island Line (WIL) tunnel connecting to an existing MTR tunnel of which a section is in clash with the new tunnel and needs to be demolished, the novel Tunnel Dismantling Machine (TDM) was developed as a unique solution with the view to mitigate construction risks. The TDM is unprecedented worldwide and is a pioneering construction method for demolishing existing segment-lined tunnels. The variable geology, constrained space, and dense urban environment of the site added to the difficulties of the project.

The TDM greatly reduce the exposure of workers to hyperbaric condition by localising the compressed air in the demolition chamber, thus constituting a major health and safety improvement. The confinement pressure necessary for ensuring tunnel face stability was achieved by the TDM using similar principles to a TBM but adapted in a different way from TBMs. Apart from removing the tunnel segment rings, the TDM was equipped for concrete spraying in compressed air. The performance of shotcrete under compressed air condition was verified by extensive trials and mix optimisations, which advanced the specialty of concrete technology. The TDM demonstrated how imaginative engineering and cutting edge technology could be used to minimise the risks and the adverse impacts to existing structures.

The innovative idea of TDM has been transformed into reality by overcoming key challenges through cross-disciplinary teamwork, non-conventional design, thorough testing and physical trials, detailed construction planning, preventive site inspections, production cycle optimisations, extensive monitoring and comprehensive contingency planning. Through a combination of meticulous planning, a highly experienced and dedicated project team, and collaborative relationship between project parties, the tunnel dismantling works progressed safely with minimal impact to third parties. The successful completion of TDM works was instrumental to the completion and opening of the MTR WIL which was awaited by the public with great interest, further, the TDM is an exemplar of engineering excellence and innovation in Hong Kong.

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Figures

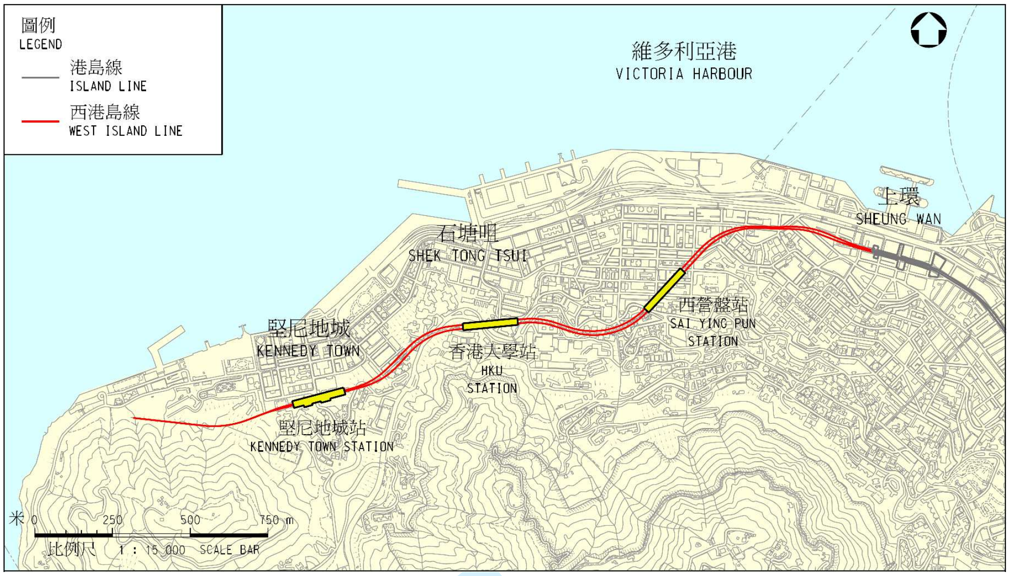


Figure 1 Layout plan of MTR West Island Line

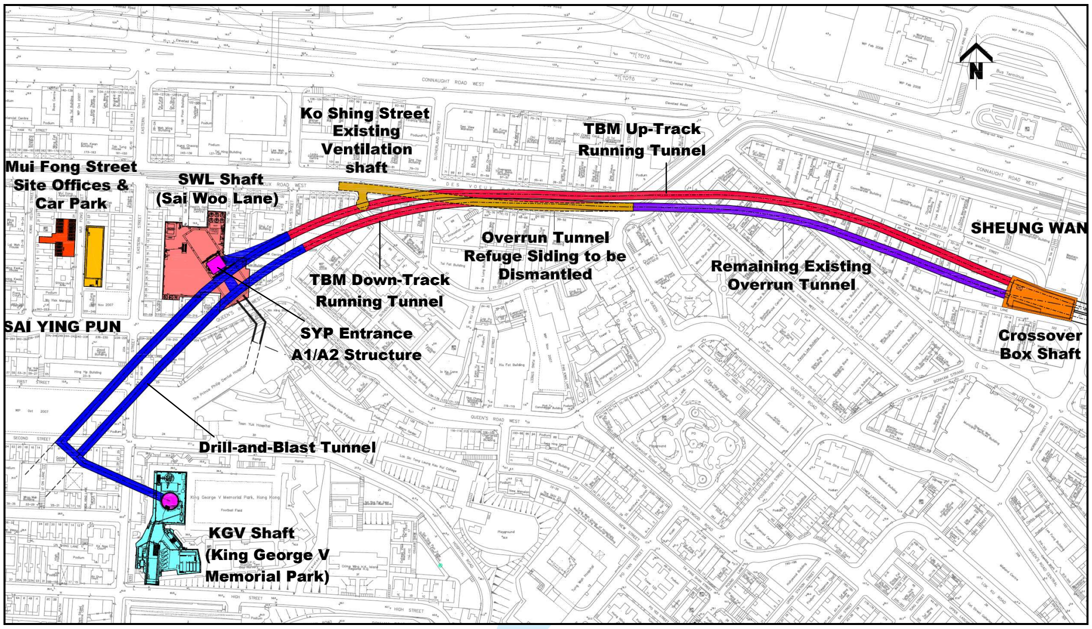


Figure 2 General layout of WIL703 project

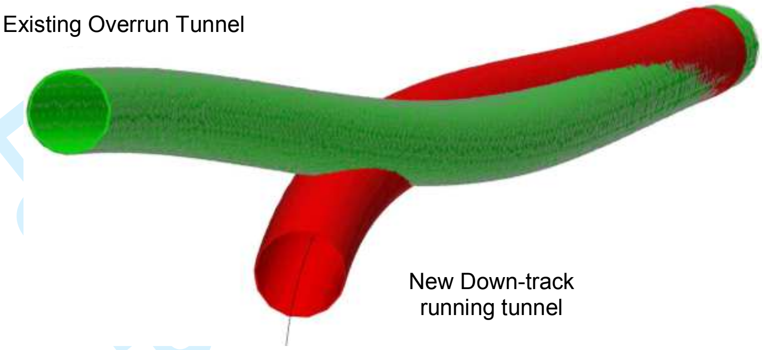


Figure 3 Geometry of new tunnel connection to existing Overrun Tunnel

Figure 4 Photograph of existing Overrun Tunnel

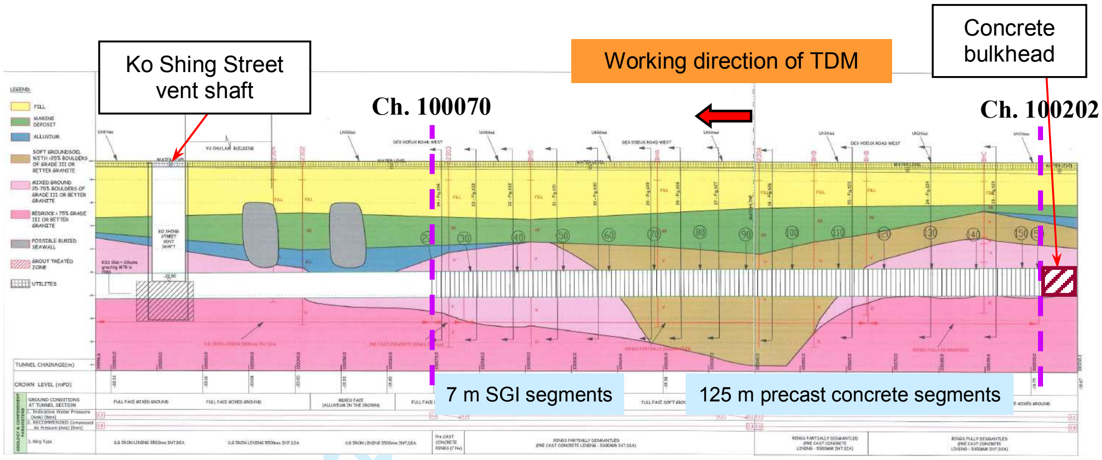


Figure 5 Geological section

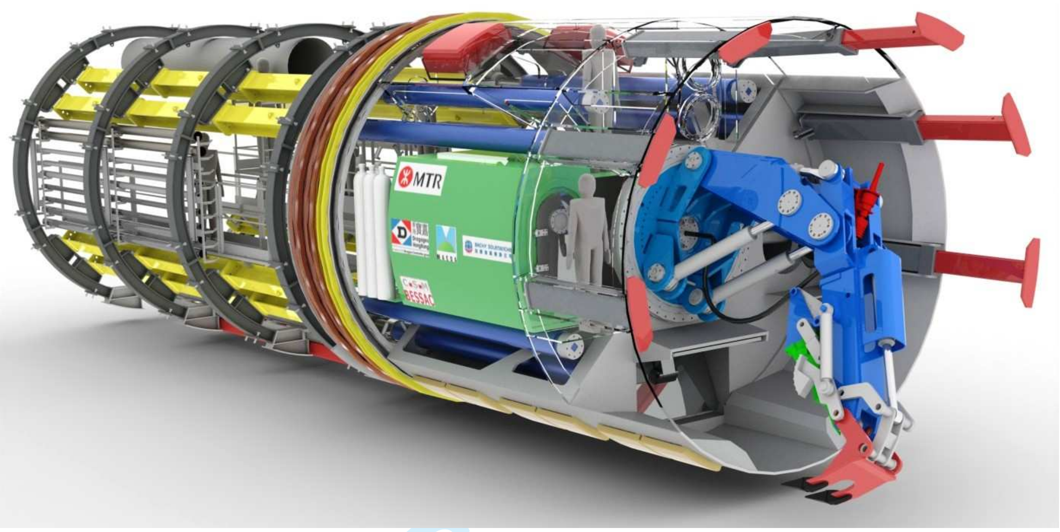


Figure 6 Conceptual view of TDM

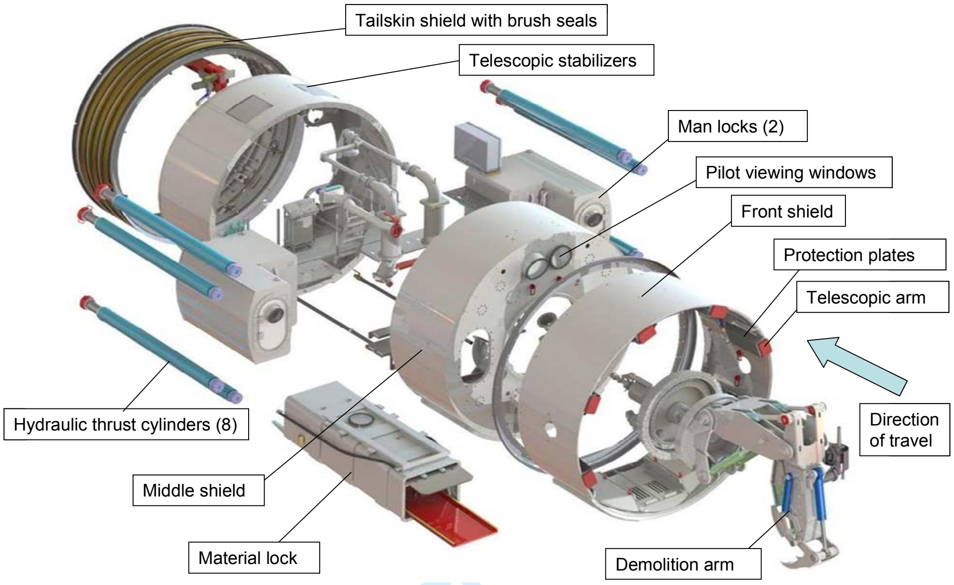
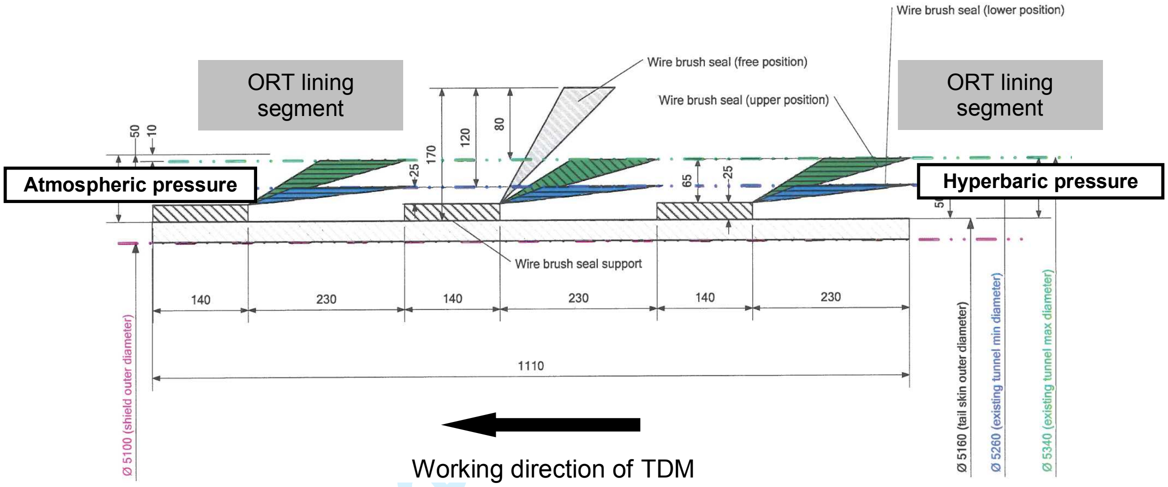
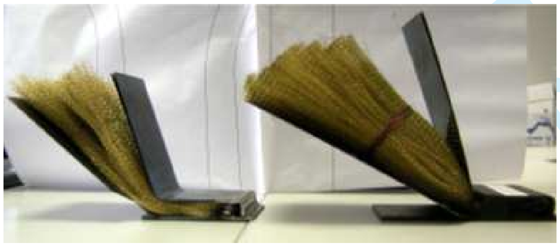


Figure 7 Anatomic view of TDM



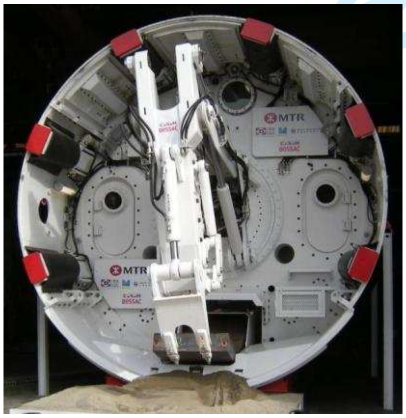


Wire brush tail seals

Figure 8 Schematic of tail skin

(a) Breaking of segment by hydraulic breaker

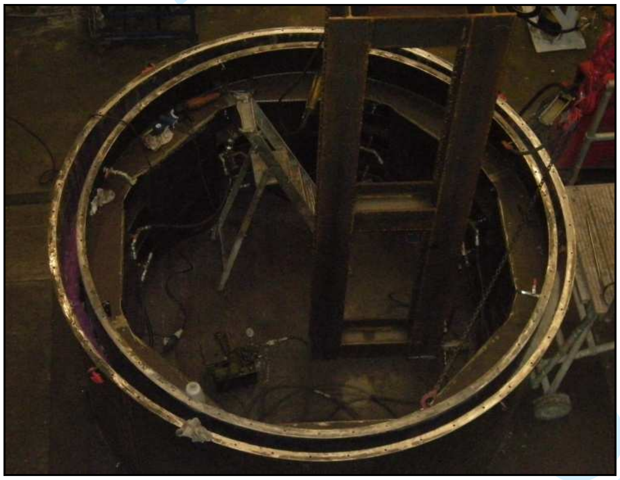
(b) Grabbing of segment



(c) Transferral of segment to material lock

Figure 9 Testing of demolition arm

(a) Wire brushes tail seals



(b) Tail skin placed in steel ring

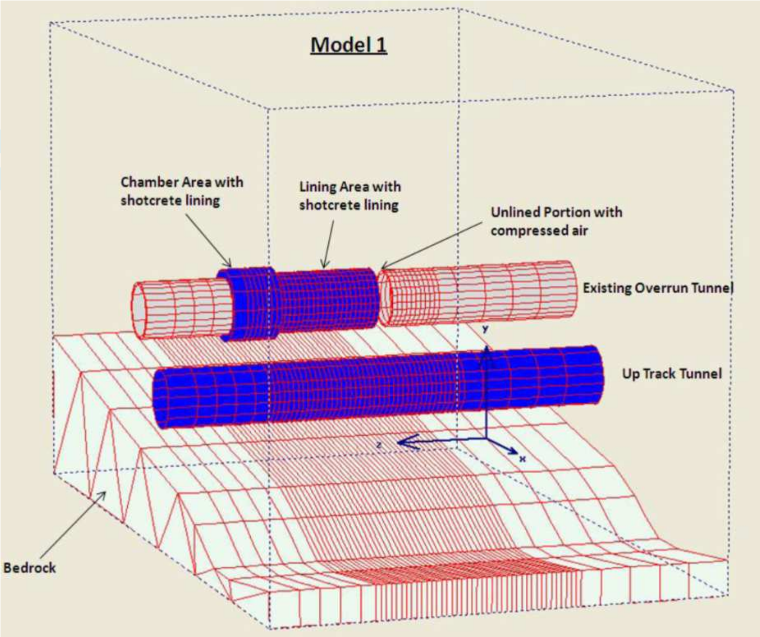
Figure 10 Testing of wire brushes tail seals

Figure 11 Pressure chamber for shotcrete trial

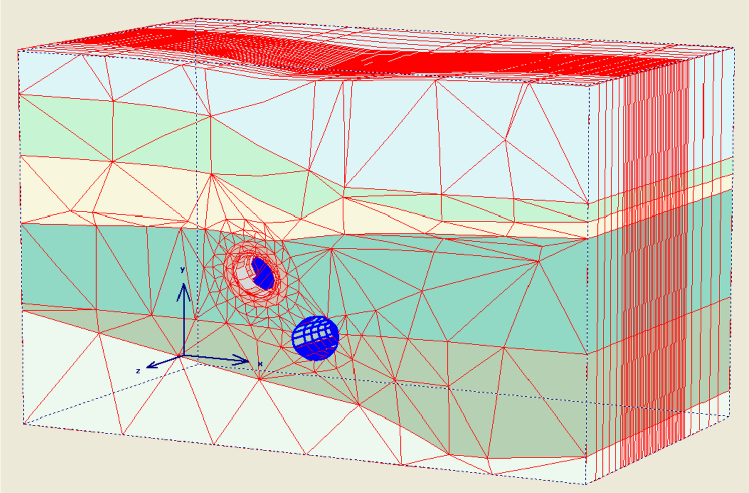
(a) Testing of hinged joint in mock-up tunnel

(b) Testing of jacking frame in mock-up tunnel

Figure 12 Mock-up tunnel for trial of TDM

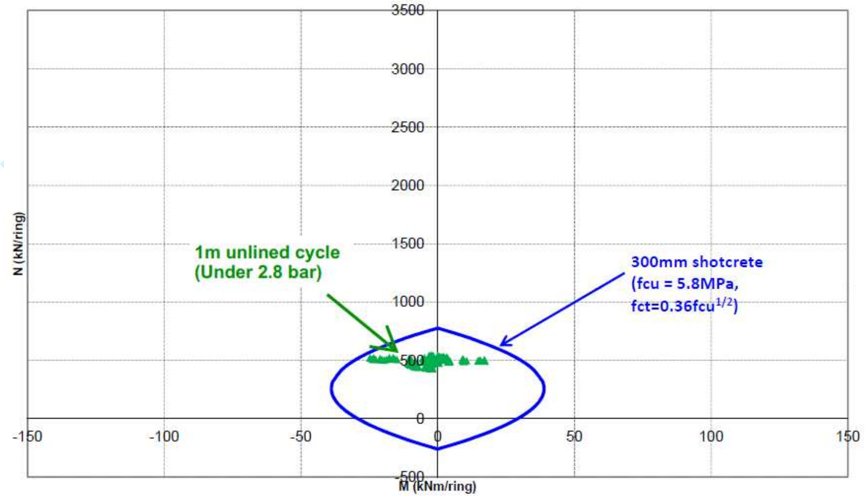


(a) 3-d finite element model

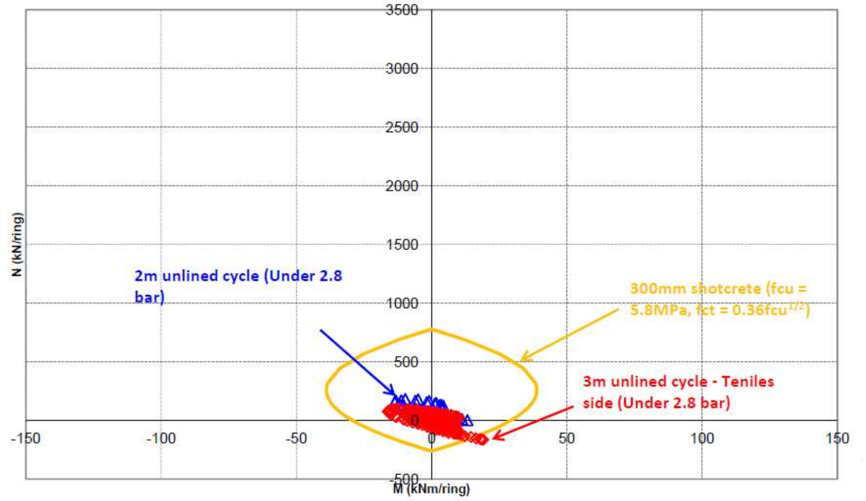


(b) Deformed shape from analysis results

Figure 13 Finite element analysis of tunnel dismantling



(a) Assessment of shotcrete lining for 1 m unlined section



(b) Assessment of shotcrete lining for 2 m and 3 m unlined sections

Figure 14 Assessment of temporary shotcrete lining

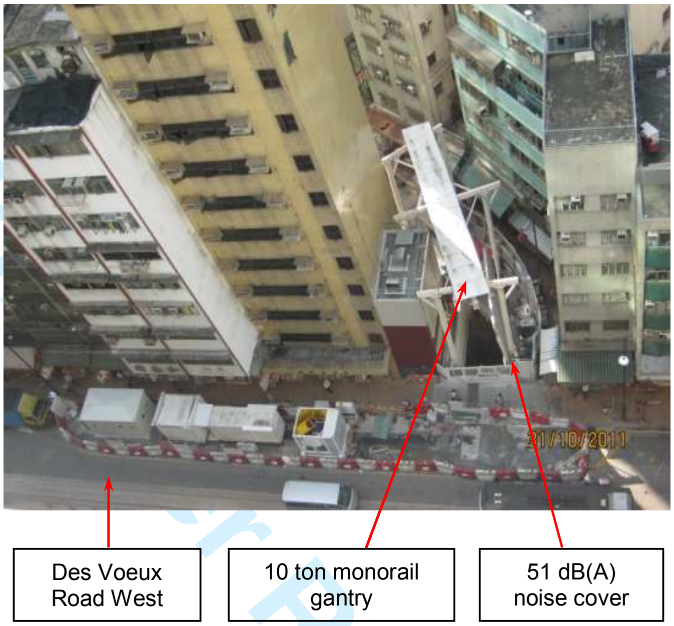
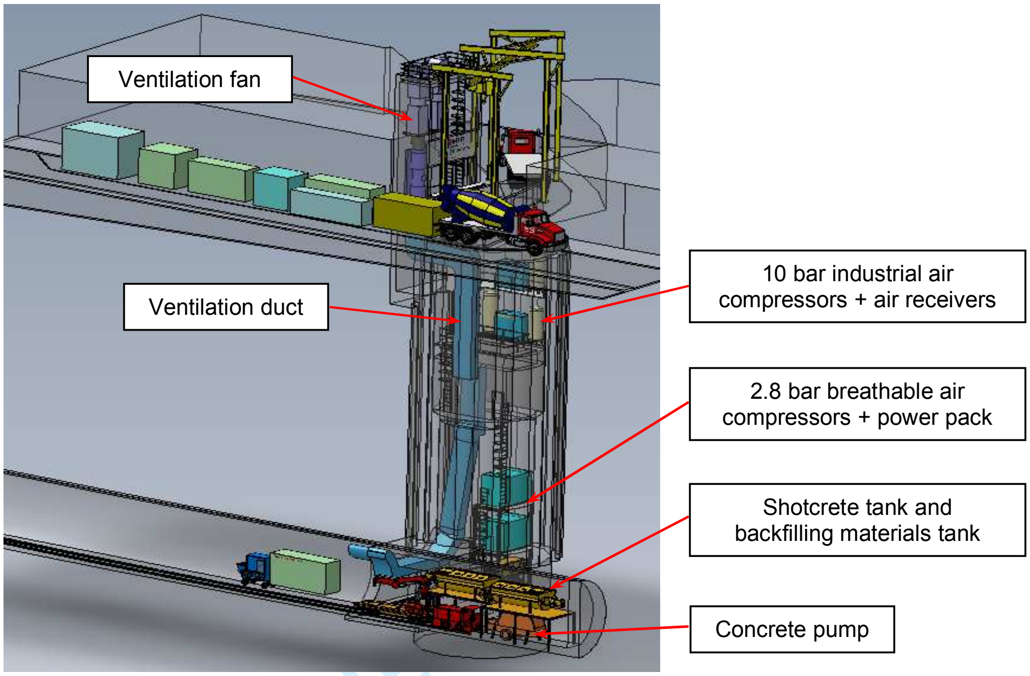
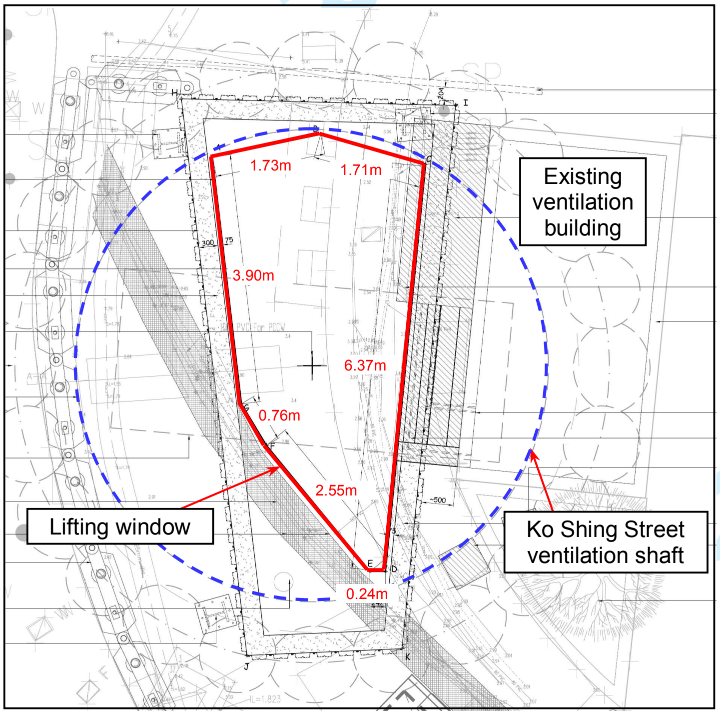


Figure 15 Site installation at ground surface



(a) Site setup in shaft and shaft bottom



(b) Lifting window of ventilation shaft

Figure 16 Site installation in ventilation shaft

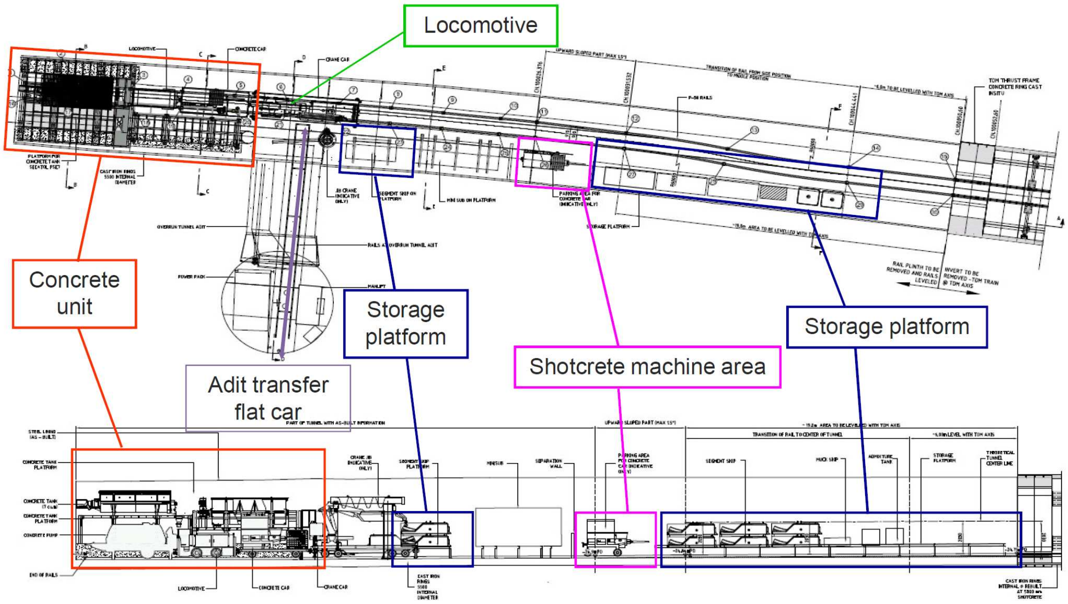


Figure 17 Site installation in Overrun Tunnel

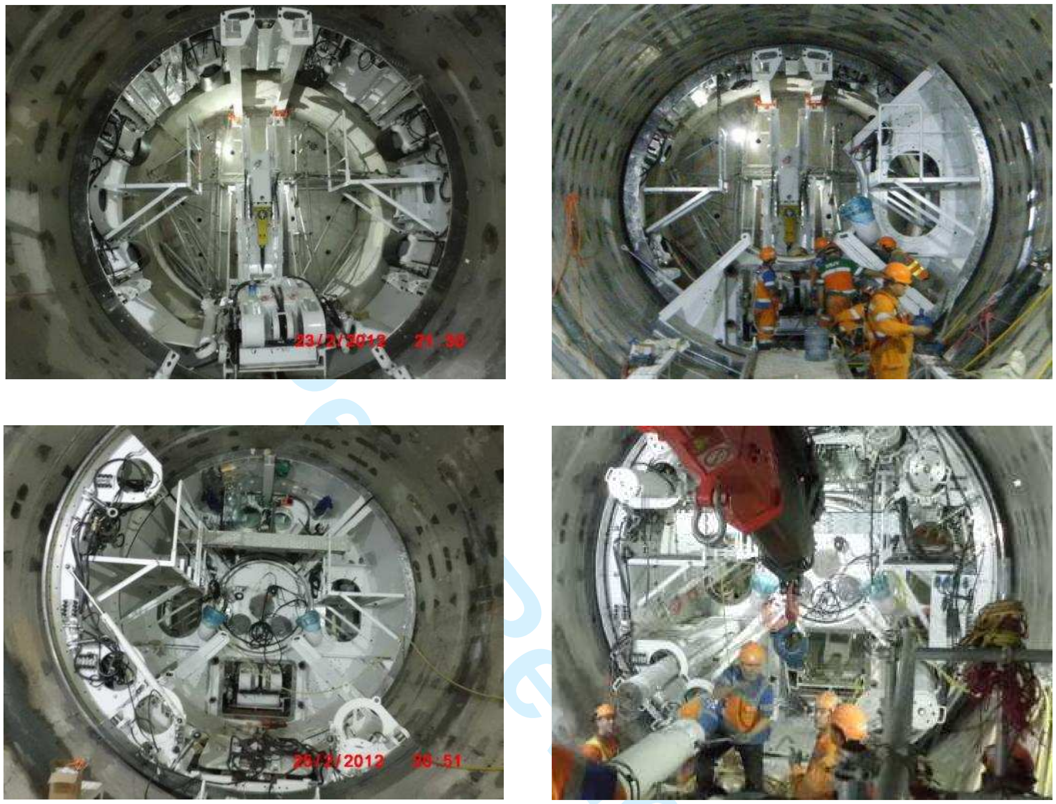
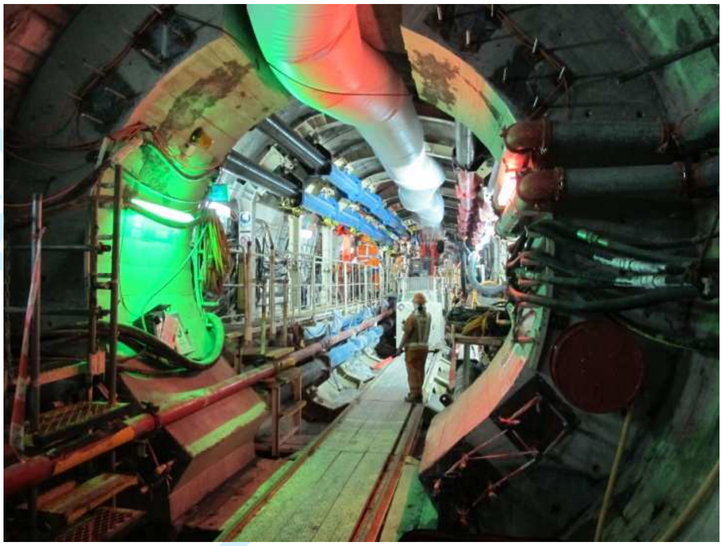


Figure 18 TDM assembly inside Overrun Tunnel

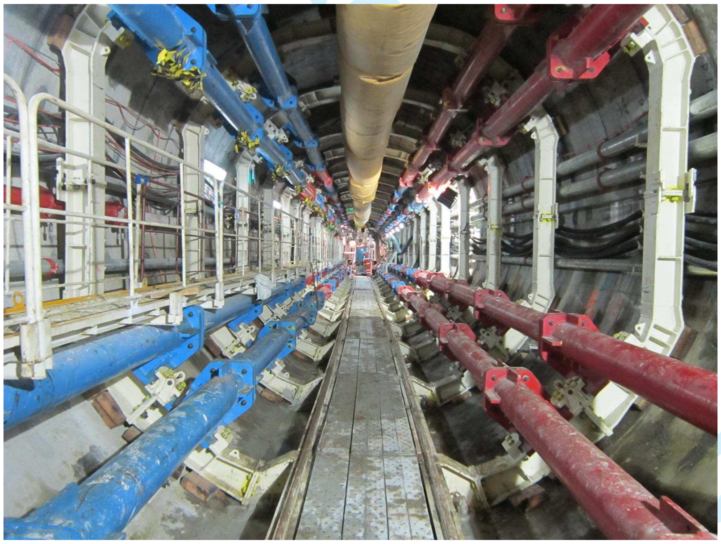
(a) Manipulating demolition arm for segment dismantling

(b) Shotcreting operation

Figure 19 Segment dismantling and shotcreting operations



(a) Reinforced concrete thrust reaction ring



(b) Steel thrust reaction frame

Figure 20 Thrust reaction structure

Figure 21 Demolition chamber during an atmospheric stop

Figure 22 Ice jacket to reduce heat stress of workers