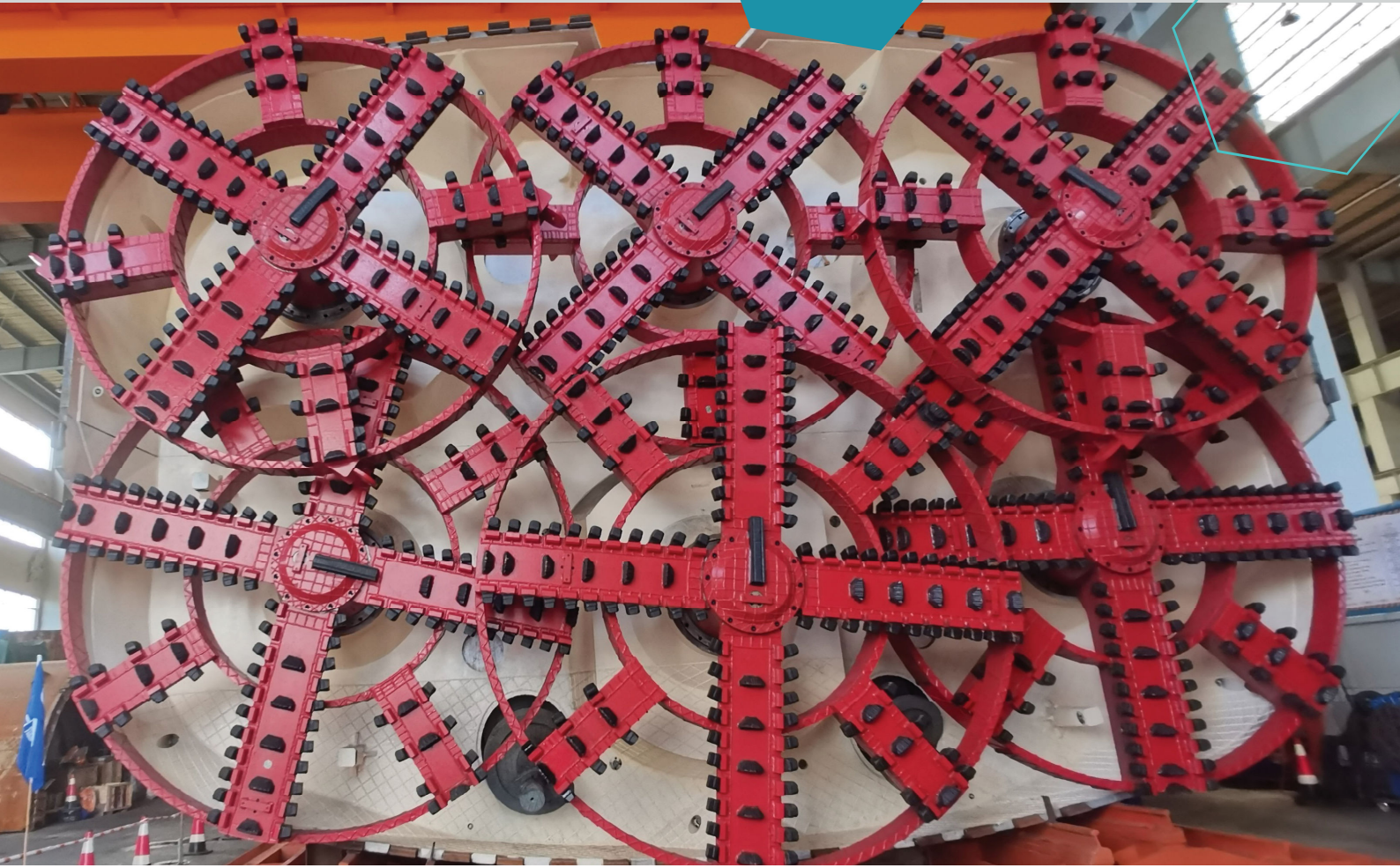




The Use of Rectangular Tunnel Boring Machine

Foreword

The successful introduction of the Rectangular Tunnel Boring Machine (RTBM) for the construction of pedestrian subways under the Kai Tak Development (KTD) represents another major milestone in adopting innovative construction methods in the Hong Kong Special Administrative Region (HKSAR). This innovative technology demonstrates advanced engineering practices, coupled with the regulatory frameworks and safety protocols of the HKSAR, effectively delivering high-quality tunnel construction works under extremely constrained urban environments. The RTBM method has proven particularly valuable in overcoming challenges posed by shallow soil cover, congested underground utilities, and heavy traffic flow in urban areas.

I would like to commend the project teams for their dedication and technical excellence in introducing RTBM to the HKSAR's unique ground conditions and performance requirements. Despite complex site constraints, including major utilities beneath Prince Edward Road East, limited working space, and tight possession windows, the teams successfully demonstrated the feasibility and advantages of mechanised rectangular tunnelling in overcoming these site constraints. Their expertise was pivotal in ensuring excavation stability, minimising ground settlement, and maintaining uninterrupted operation of critical public infrastructure throughout the works.

My sincere appreciation is also extended to the consulting engineers whose collaborative efforts were essential to this breakthrough. The adoption of RTBM not only enhanced construction safety and minimised surface disruption, but also ensured programme certainty through risk mitigation. These advantages mark a significant step towards expanding HKSAR's capability to adopt an innovative tunnelling technology in congested urban areas with less disruption to the public throughout the construction period.

As the HKSAR continues to pursue resilient, smart and sustainable infrastructure, CEDD remains committed to fostering innovation in underground construction. This publication consolidates the experience gained from the construction of pedestrian subways in the KTD, including the key lessons learnt and technical insights that will benefit future applications. It is intended as a useful reference for engineers, contractors, and stakeholders planning to adopt RTBM for the construction of pedestrian subways, utility tunnels, and other underground structures with shallow soil cover across the territory.



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Disclaimer

This publication is intended solely for informational and experience sharing purposes. It should not be regarded as a mandatory handbook or comprehensive set of procedures. It does not constitute part of the official contractual documentation or mandatory requirements. Users are advised to consult the relevant standards, regulations, and contractual provisions applicable to their specific projects. CEDD assumes no liability for any actions taken or decisions made based on this publication.

Acknowledgement

CEDD has advanced the application of RTBM in the HKSAR through the successful delivery of the pedestrian subway construction works under the KTD projects. Their continuous support, technical guidance and commitment to innovation were instrumental in establishing RTBM as a viable method for tunnel construction in urban area with heavy traffic flow, congested and aged underground utilities, and shallow soil cover. The authors express sincere appreciation for their leadership and fostering a collaborative environment conducive to engineering excellence.

Gratitude is also extended to the project consultant, AECOM Asia Co. Ltd., whose technical expertise and design support contributed significantly to the refinement of RTBM construction and monitoring requirements. The main contractor and its joint venture teams, namely Build King Civil Engineering Limited and Shanghai Tunnel Engineering Co. Limited, are acknowledged for their professionalism, dedication and successful execution of the mechanised tunnelling works. Special thanks are due to the equipment manufacturers and system suppliers involved in the design, fabrication and commissioning of the RTBM.

Acknowledgment is further given to the specialist subcontractors responsible for ground investigation, grouting works, instrumentation and monitoring, and site supervision. Their contributions were essential in ensuring the stability of ground conditions, the accuracy of monitoring data and the effective management of tunnelling risks. Lastly, appreciation is extended to all site personnel, engineers, safety officers and technicians whose collective effort, perseverance and commitment to high standards of workmanship were vital to the successful implementation of this initiative.

Executive Summary

This publication provides a comprehensive technical framework for the adoption and implementation of RTBM in the construction of pedestrian subways in urban area with heavy traffic flow, congested and aged underground utilities, and shallow soil cover. RTBM represents a substantial advancement over traditional cut-and-cover and mined excavation methods. It also offers enhanced control of ground behaviour, improved construction safety and significantly reduced disruption to road traffic and underground utilities. The method is particularly suitable to the highly constrained underground conditions in Hong Kong, where shallow soil cover, congested and aged underground utilities and limited working space pose significant challenges to conventional construction.

The document outlines key considerations for RTBM deployment, including site constraints and considerations, design and characteristics of RTBM, construction sequence including ground improvement works and safety concerns, and monitoring requirements. RTBM allows precise control of face pressure by injection of soil conditioning and continuous deformation surveys, resulting in minimal ground settlement as compared with traditional excavation. The adoption of rectangular precast tunnel segments further contributes to construction efficiency and dimensional accuracy, improving long-term structural integrity. This method considerably improved ground stability, and minimised risks associated with major underground utilities.

The Stage 5B project is part of the KTD for infrastructure works at the former north apron area. The contractor of this project adopted RTBM for construction of a pedestrian subway across Prince Edward Road East. Throughout this publication, there is comparison between the RTBMs adopted in the Stage 5B project and the Stage 3B project (an earlier project under the KTD which was the first adoption of RTBM in Hong Kong and with a smaller RTBM cross-sectional area as compared with the Stage 5B project). Key lessons learnt include the importance of early ground investigation, real-time integration of RTBM and ground monitoring data via a Visualisation and Data Management System, meticulous planning of launching and retrieval shafts, and the need for a competent workforce familiar with mechanised tunnelling operations.

This publication establishes a reference standard for future RTBM applications, defining technical expectations for design, construction, monitoring, safety management and risk mitigation. As urban development continues to intensify and demand for underground space increases, RTBM provides a reliable, safe and low-impact solution for delivering pedestrian subways and underground structures in Hong Kong.

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1. Objective of This Publication

This publication sets out the design considerations, construction sequence, operation controls, monitoring system and safety provisions for the application of RTBM in the construction of underground pedestrian subways in congested urban environments.

This publication summaries key considerations of RTBM aiming to:

- a. provide a unified reference framework for government departments, consultants, contractors, and industry practitioners in the designing of RTBM, operating and monitoring during the RTBM drive.
- b. promote safe, reliable, and efficient deployment of RTBM in congested urban environments, particularly where traditional cut-and-cover or mined tunnelling methods pose significant risks due to limited working space, congested underground utilities, traffic constraints, or the presence of existing structures.
- c. consolidate lessons learnt and best practices from completed RTBM projects in Hong Kong, providing guidance on the suitability, advantages, and limitations of RTBM for future applications.

The requirements of this publication shall supplement but not supersede statutory provisions, codes of practice, and contract documents. Where discrepancies arise, the more stringent requirement shall apply.

2. Background for Adoption of RTBM Technology

The adoption of RTBM technology has emerged as a critical solution for constructing pedestrian subways and other underground structures, such as vehicular tunnels and underpasses, in urban areas with heavy traffic flow, congested and aged underground utilities, and shallow soil cover. This chapter outlines the engineering rationale, site constraints, comparative method selection considerations, and the fundamental characteristics of RTBM that justify its use in modern urban tunnelling practice.

2.1. Site Constraints

In the Stage 5B project, the pedestrian subway to be constructed is 86m long, routed underneath the Prince Edward Road East (PERE), one of the red traffic routes in Hong Kong, and Sa Po Road, and across 12 traffic lanes as shown in Figure 1 and Figure 2. The clearance between the subway and the pile foundation of existing flyovers was as close as 2m only. The subway also passed under high voltage electric cables, numerous major water-bearing utilities, including water trunk mains built in 1960s. Construction of this subway using conventional trenchless methods would greatly aggravate the risks to works safety, adjacent facilities, and the residents nearby if conventional trenchless methods were applied.



Figure 1 - Layout Plan of Subway

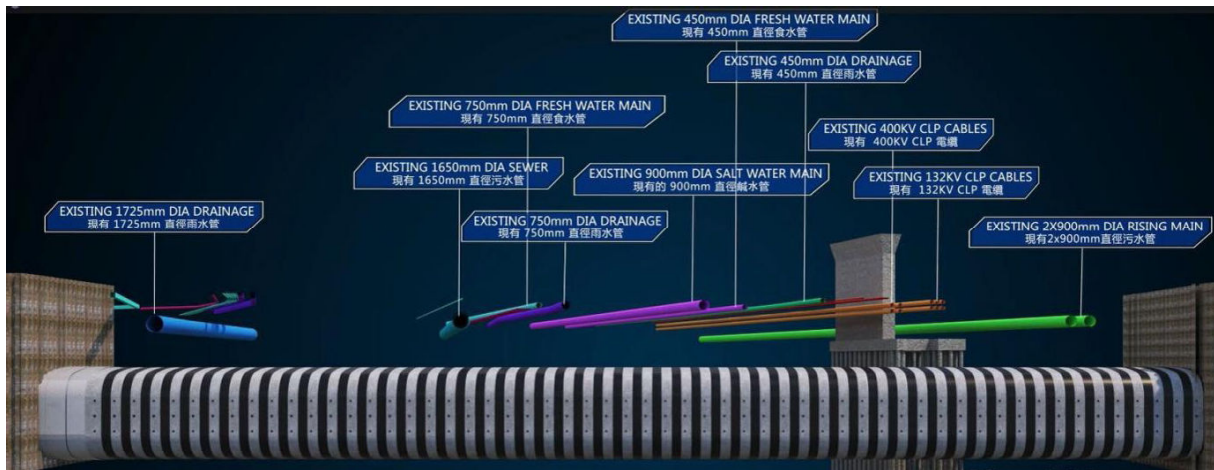


Figure 2 - Underground Utilities and Structures along Subway

2.2. Selection of Construction Method

To suitably overcome the site constraints as described in the previous paragraph, different construction methods including the conventional cut-and-cover method, mined tunnelling, the construction by circular Tunnel Boring Machine (TBM) or the construction by RTBM had been considered. By taking into account the geotechnical and hydrogeological conditions, settlement control requirements / criteria, utilities and other physical constraints such as piled foundation of highways structures in vicinity to the tunnel alignment, available space for shaft construction, environmental requirements, and project duration, construction by RTBM is considered to be the most suitable option.

The construction by RTBM is particularly suitable for tunnel construction beneath arterial roads, major junctions, public open spaces, and commercial or residential districts. This mechanized trenchless method minimises disturbance of traffic at ground level and requires only limited working spaces for construction of launching and retrieval shafts.

In the Stage 5B project, the subway was to be constructed in close proximity to existing piled foundations. This constraint limited and reduced the permissible excavation envelope, rendering conventional open-cut or mined tunnelling methods highly risky or even impracticable. The RTBM has the advantage of excavating through narrow horizontal and vertical clearances without affecting adjacent structures. Moreover, in densely populated urban districts where construction noise, vibration, dust, and traffic disruption must be kept to a minimum, the RTBM construction generates low environmental impact and supports community-friendly and safety-oriented construction practices.

The following paragraphs presented a more detailed comparison between the RTBM and other construction methods for the use in the Stage 5B project.

2.2.1. Comparison of RTBM with Cut-and-Cover / Mined Tunnelling Methods

An RTBM was a shielded mechanised tunnelling system designed to excavate a full-face rectangular profile and provide immediate ground support and also enable synchronous installation of tunnel segments. The system was capable of maintaining stable face pressure, controlling ground loss, and operating safely in shallow soil cover (generally equivalent to one times the tunnel height) during excavation within congested urban environments.

RTBM was considered to be more suitable for use in the Stage 5B project than conventional construction methods such as cut-and-cover method or mined tunnelling method due to the following conditions:

- a. surface activities had to remain operational, and prolonged road closures were unacceptable;
- b. large-scale decking or traffic diversion works were impractical;
- c. utility diversion was time-consuming, risky, costly, or infeasible;
- d. shallow soil cover limited allowable ground deformation;
- e. excessive settlement of roads and highway structures was unacceptable as it would have caused critical damage to underground utilities and disrupt live traffic;
- f. a rectangular cross-section was required for functional or operational reasons;
- g. adequate space was available for shaft construction;
- h. the subway alignment was generally straight both horizontally and vertically; and
- i. high predictability and repeatability of excavation behaviour were required.

The RTBM equipped with pressure-balanced excavation provides superior control in soft, loose, or mixed ground, significantly reducing ground loss and settlement. This made the RTBM suitable to be used in settlement-sensitive zones, across major transportation corridors, and at locations with stringent performance requirements on surface, such as PERE where heavy traffic flow is encountered, and structural deformation, such as in the vicinity of footing foundations of highways structures.

As compared with cut-and-cover excavation, the RTBM has the following advantages:

- greatly reduce surface disruption and visual impact;
- minimise land-take and temporary decking;
- reduce interference with existing utilities and services; and
- enhance public and worker safety by limiting open excavations.

As compared with conventional mined tunnelling, the RTBM has more advantages as listed in Table 1.

Table 1 Comparison of Conventional Mined Tunnelling with RTBM

Items	Conventional Mined Tunnelling with Cast in-situ Concrete Structure	RTBM Trenchless Method with Precast Concrete Tunnel Segments
Working Environment inside tunnel	Dust and emissions from generators	Minimise dust by mixing slurry with excavated soil Minimise emissions by use of electrical machine
Groundwater Ingress	Potential risk of groundwater ingress, requiring extensive grouting works	Special design of waterproofing system to reduce groundwater inflow significantly
Safety of Workers	Potential safety hazards due to working in confined spaces and operating machinery for excavation and ground treatment	No man-entry required during excavation by RTBM which is operated by workers in control room
Lifting Operations inside Tunnel	Difficult to erect hanger for lifting operations	Precast tunnel segments are adopted to eliminate lifting operations inside tunnel
Impact to Adjacent Underground Utilities, Roads and Structures	Risk of over-excavated which may cause undue settlement or movement of underground utilities or structures	RTBM cutterhead is equipped with sensors to monitor face pressure so as to minimise over excavation
Progress of Excavation Works	Estimated to take 7 months to construct the subway under the Stage 5B project	Actual duration of 45 days (approximately 1.5 months) for subway construction under the Stage 5B project

2.2.1. Comparison of RTBM with Cut-and-Cover / Mined Tunnelling Methods

In the aspect of geometry, an RTBM directly forms a rectangular profile that matches the functional requirements of pedestrian subways, equipment corridors, and utility tunnels. A circular TBM inherently generates circular profile, resulting in unused corner spaces and often requiring additional works to form flat floors and usable sidewalls. Tunnel formed by circular TBM usually requires secondary works including trimming of invert or crown, construction of flat slabs for pedestrian passage, formation of plinths for Mechanical, Electrical, & Plumbing (MEP) systems, and locally thickened linings. These secondary works extend the construction programme and increase both cost and material usage. RTBM eliminates or substantially reduces such modifications by forming the final usable cross-section during excavation.

Regarding the control of ground loss and settlement performance, circular tunnels tend to relax ground stresses around the curved crown, particularly under shallow soil cover, potentially resulting in greater settlement if not carefully controlled. RTBM, with its flatter roof profile and pressure-controlled excavation, can reduce bending of the ground arch and improve settlement performance.

The configuration of RTBM for narrow spaces is primarily achieved through its superior spatial efficiency compared to a circular TBM. Since the functional requirements for pedestrian subways are rectangular, the internal usable space of a circular tunnel is inherently smaller than that of a rectangular tunnel with the same external dimensions. To achieve the same usable space, a circular TBM will excavate a significantly larger footprint to accommodate the same "functional box" leading to "wasted volumes" above the ceiling and below the floor as shown in Figure 3. The spatial efficiency of RTBM also means that in congested urban environments where underground conditions are constrained by existing utilities and pile foundations, the adoption of RTBM is more suitable as the rectangular excavation profile directly matches the required functional envelope.

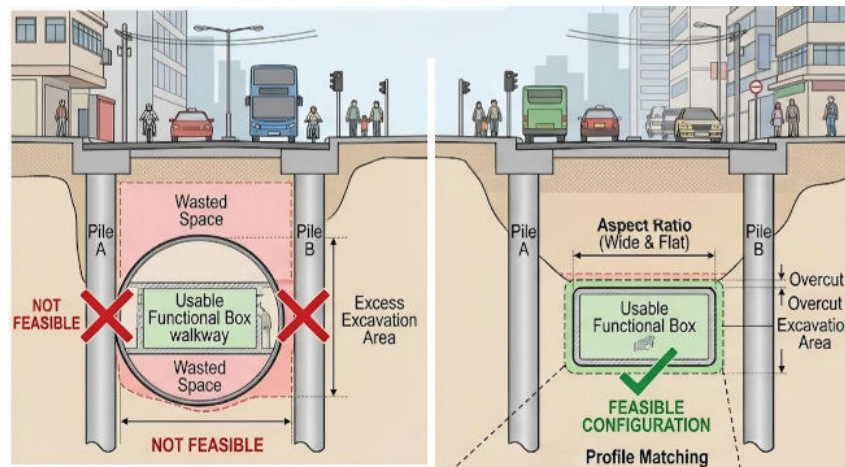


Figure 3 - Comparison of Usable Space Between Circular and Rectangular Tunnels

The associated linings of circular TBM consist of several curved segments per ring with complex jointing and gasket arrangements. In contrast, RTBM allows the use of monolithic or simplified rectangular tunnel segments, providing faster installation cycles, fewer joints, and simpler waterproofing details.

For short to medium-length (ranging from 100m to 400m) tunnel construction, RTBM offers significant advantages, including shorter mobilisation time, minimal secondary structural works, and enhanced settlement control whereas circular TBM remains more advantageous for long tunnels where continuous advance and lining systems are required. In addition, RTBM is both technically and economically superior due to the spatial efficiency of its rectangular profile, which matches with the structural shape of pedestrian subway, and the ability of the tunnel jacking method to maintain high productivity over these distances without requiring the extensive backup infrastructure associated with circular TBM.

2.3. Characteristics of RTBM

The models of RTBM adopted in the Stage 5B and Stage 3B projects were shown in Figure 4.



**Figure 4 - RTBM Model under KTD Projects
(Left: Stage 5B project, Right: Stage 3B project)**

Both RTBMs adopted in the Stage 5B and Stage 3B projects comprised the following principal components:

- Rectangular cutterhead assemblies, including cutting tools and scrapers covering the entire excavation face;
- Shield skin and structural frame, providing confinement to the surrounding ground and maintaining machine alignment;
- Face-support and soil-conditioning system, such as Earth Pressure Balance (EPB) chambers, bulk and liquid additives, to stabilise the face;
- Muck extraction system, consisting of one or more screw conveyors and associated discharge arrangements;
- Propulsion system, including main jacks and, where necessary, intermediate jacking stations for long drives;
- Lining erection system, designed to install monolithic or segmental rectangular tunnel segments within the shield tail;
- Guidance and monitoring system, incorporating laser guidance, inclination sensors, pressure transducers, torque and thrust monitoring, and other instrumentation required for safe operation.

RTBM is suitable for a wide range of soft and decomposed ground conditions commonly encountered in urban areas, including fill (FILL), alluvial deposits (ALL), marine deposits, and completely decomposed granite (CDG), as well as mixed-face conditions which directly dictate the cutterhead design; cutting tool selection; choice of mucking arrangement and other associated equipment used for tunnel excavation. Appropriate soil conditioning, face-pressure control, and advance lubrication system were adopted to ensure stable tunnelling performance under these conditions.

RTBM is designed to integrate closely with the adopted tunnel segments system. The geometry of the cutterhead and shield matched the external dimensions of the tunnel segments, allowing the segments to be installed within the shield tail under suitable tail-seal and grout conditions. This integration enables direct formation of the permanent tunnel structure with minimal secondary works and provided a continuous, watertight and durable tunnel envelope.

3. Design and Manufacture

3.1. Ground Investigation

Ground investigation (GI) was taken to establish soil stratigraphy, engineering parameters, groundwater conditions, and obstructions along the tunnel alignment. The information obtained facilitated the design of the RTBM, tunnel segments, face-pressure control measures, soil conditioning requirements, and construction sequence.

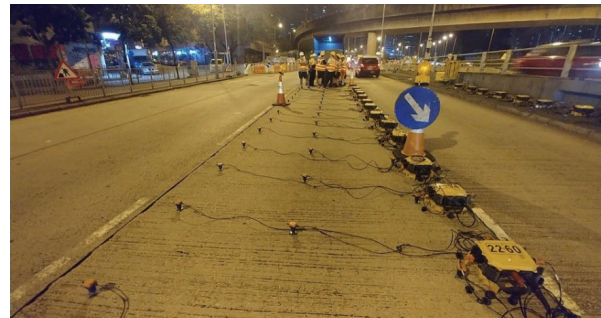
GI for RTBM projects contained boreholes, trial pits, collection of samples, and in-situ tests to determine the variability of ground conditions, together with laboratory testing to assess shear strength, compressibility, permeability, particles size distribution and Atterberg limits. Groundwater monitoring equipment were also installed to establish seasonal fluctuations, while special attention was given to identifying utilities, buried obstructions, old foundations, boulders, or mixed-face zones.

The following soil properties were determined for the use in RTBM design, and also for designing soil conditioning agents such as sodium silicate, polymer, or bentonite for the use during tunnelling operation.

- plasticity index and moisture content;
- cohesion and friction angle;
- undrained shear strength for soft clay;
- permeability and groundwater pressure;
- density and unit weight of soil;
- abrasively for cutter selection.

To supplement the boreholes and laboratory testing results, a geophysical survey was undertaken in the Stage 5B project to improve the spatial resolution of subsurface variability. This enhancement was introduced based on lessons learnt from the previous Stage 3B project, where several geological transitions, particularly between FILL, ALL and CDG, were encountered earlier or more abruptly than indicated by the borehole spacing. Such transitions contributed to torque fluctuation, inconsistent face stability, and early ground relaxation during tunnelling operation.

The geophysical survey was a non-intrusive method to refine the interpretation of soil interfaces, identify buried obstructions, and delineate irregular pockets of contrasting stiffness that may affect the RTBM performance. The survey was carried out at nights for all traffic lanes of PERE, see Figure 5.



Non-destructive method to identify any obstruction along the proposed tunnel alignment by seismic system

Sensors placed along PERE to transmit and receive seismic pulse

Figure 5 - Geophysical Survey on Prince Edward Road East

The survey involved use of ground-penetrating radar (GPR), electrical resistivity imaging (ERI), and seismic refraction profiling at areas covering the tunnel alignment. These methods provided continuous subsurface profiles that complemented the point-based information from boreholes. The geophysical survey enabled:

- improved mapping of FILL / ALL and ALL / CDG transitions,
- early identification of potential boulders, cobbles or remnants of old foundation structures,
- detection of voids or loose zones within reclaimed materials,
- refinement of groundwater level interpretation when correlated with piezometer data.

The enhanced ground model resulting from the geophysical survey formed an important input for the RTBM design in the Stage 5B project. It supported the calibration of earth pressure and conditioning agent requirements, optimisation of cutterhead configuration, and establishment of face-pressure envelopes for different geological zones. The survey result also provided underground information for establishing the location to install settlement markers for subsequent monitoring proposal of tunnelling works.

3.2. Design of Tunnel Segments

Rectangular tunnel segments were designed to provide structural resistance to earth pressure, hydrostatic pressure, jacking forces, and operational loads while maintaining geometric precision of the tunnel. The loading included earth pressure and water pressure on segments' walls, surcharge from traffic and structure foundations, RTBM jacking thrust distribution, and also temporary loads during segment erection had been taken into account in the design.

Rectangular tunnel segments could be in form of a monolithic precast unit (single-piece rectangular segments) or a multi-panel precast tunnel segment (divided into base, walls, soffit panels). In the Stage 5B project, monolithic unit as shown in Figure 6 below was adopted since there was sufficient working area to cast the whole tunnel segments on site and transportation of the tunnel segment via public road was not required. The monolithic design ensures higher structural rigidity, reliable water-tightness and a faster construction cycle.

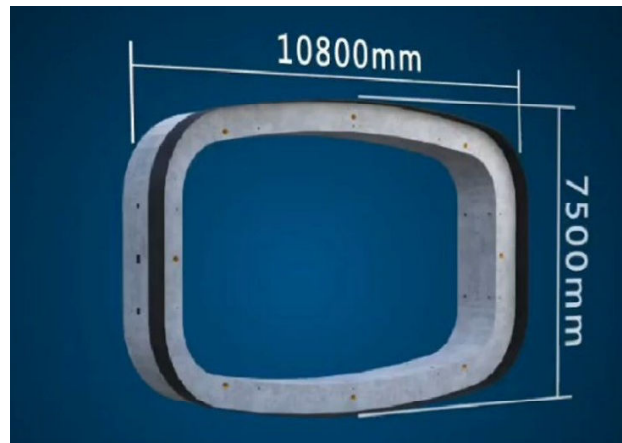


Figure 6 - RTBM Rectangular Tunnel Segments Geometry

The tunnel segment consisted of tail seal, gaskets, hydrophilic strip, and post-grouting tubes for providing the required water-tightness of tunnel barrel. Based on the experience gained in the design of precast concrete segments for the previous Stage 3B project, the waterproofing system was further enhanced in the Stage 5B project by provision of a number of 15mm diameter grout pipes around each precast concrete tunnel segment for grouting works. Furthermore, additional gasket and joint sealant was provided between the concrete and steel collar, and hand-held pins between adjacent segments were also installed to enhance the waterproofing and tightness of the tunnel segments. Shear keys and dowels were incorporated in the tunnel segments to further enhance the connection between tunnel segments and structural continuity, and to ensure minimal deviation between tunnel segments and the tunnel alignment.

3.3. Design of RTBM

The RTBM was designed to suit the geometric, environmental, geotechnical and operational requirements of the subway construction in the KTD Area. This section outlined the design considerations developed from industry practice, experience gained from the previous Stage 3B project (the first RTBM adopted in the Hong Kong for construction of a pedestrian subway across Choi Hung Road and PERE), and the requirements from relevant departments of the HKSAR Government.

The RTBM should be designed to ensure safe support to the excavation face, predictable ground behaviour, structural integrity, efficient segments installation, minimal ground settlement, and full functional compatibility with site constraints. The components of RTBM were illustrated in Figure 7.

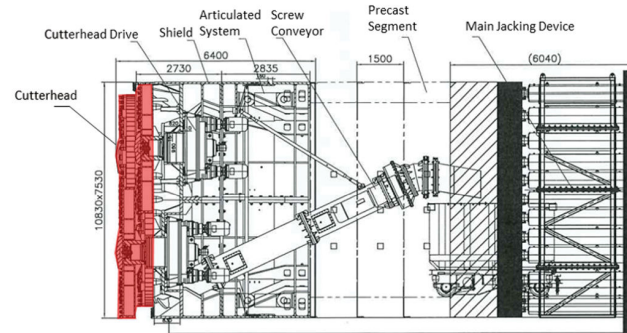


Figure 7 - Design of RTBM Cutter Heads - Cutterheads Arrangement

3.3.1. Design of Cutter Tools

Cutter tools should be selected in accordance with local ground characteristics. In the Stage 5B project, the RTBM encountered strata of FILL, ALL and CDG. Such variable strata required drag bits for soft soil, tungsten-carbide picks for CDG pockets, reinforced corner cutters to maintain rectangular geometry, and additional scraping tools to avoid clogging when the RTBM was being operated at a face pressure lower than the designed face pressure. The cutter arrangement had been designed to cover the full excavation face such that there is no “blind corners” which could cause uneven cutting during the RTBM drive.

The primary lesson learnt from the Stage 3B project was that the highly cohesive clayey alluvium and the presence of unforeseen cobbles or boulders could lead to cutterhead clogging and accelerated wearing of tools. To overcome the above-mentioned challenges in the Stage 5B project where the RTBM excavation face was significantly larger than that in the Stage 3B project, the cutterhead design in the Stage 5B project was substantially enhanced. A significantly larger number of scrapers were deployed to improve soil breaking and mixing efficiency, thereby preventing the formation of “mud cakes” at the cutterhead and tunnel face, as shown in Figure 8. Additionally, tungsten-carbide rippers were installed between the scrapers to provide robust crushing capabilities for cobbles and hard pockets. These cutting tools featured specialised anti-wear insert welding to ensure durability and maintain excavation stability throughout the drive. The comparative arrangements of scrapers and rippers for the Stage 3B and Stage 5B projects are illustrated in Figure 9 and Figure 10, respectively.



Figure 8 - “Mud-Cake” at Cutterhead (photo taken from other project)

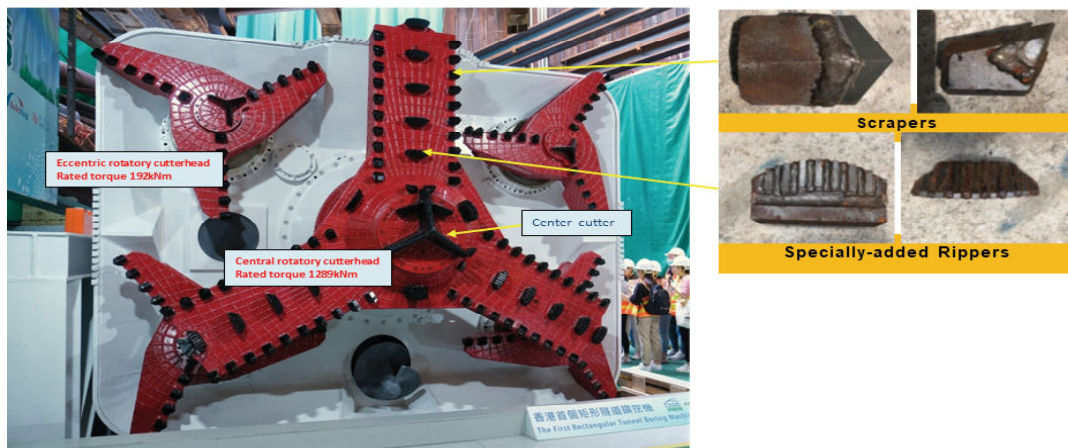


Figure 9 - Scrapers and Specially-added rippers on the cutterhead in Stage 3B RTBM



Figure 10 - Enhanced Design of Scrapers on the cutterhead in Stage 5B RTBM

3.3.2. Cutterhead Arrangement

Unlike Circular TBM, the RTBM cutterhead must match a rectangular excavation footprint. In this Stage 5B project, the cutterhead consisted of 6 nos. of cutterdisks with larger diameter of 4m or 4.2m to cater for the larger area of excavation as shown in Figure 11 and asymmetrical shaping to maintain face pressure uniformity. Due to the increased cutting resistance at the edges of a rectangular face, the RTBM was equipped with high-torque motors to avoid torsional imbalance. Therefore, the cutterhead included scrapers and anti-clogging ribs, enlarged openings for muck transfer, and secondary agitation paddles for homogenisation.

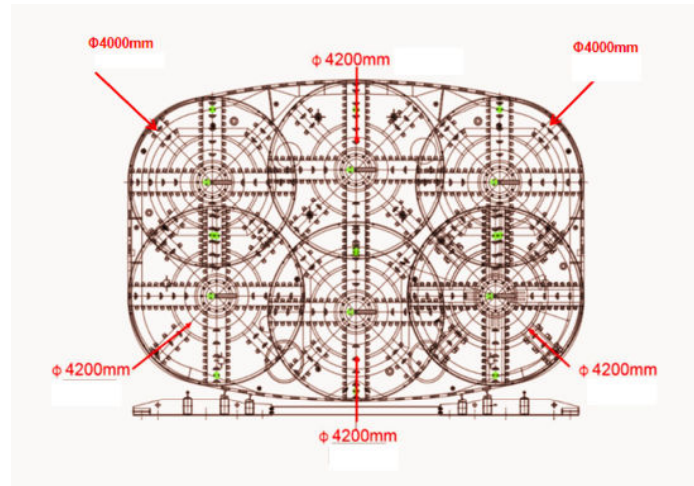


Figure 11 - Cutterhead Arrangement of the RTBM

The tunnel was to be constructed with shallow soil cover (6.0m soil cover at critical location which is about 0.8 of the vertical height of the RTBM, less than the normal 1.0-diameter soil cover required for TBM operation) and in vicinity to many sensitive utilities. Maintaining a precise earth pressure balance during the RTBM operation is critical. Wearing condition of the cutter must be rigorously monitored because worn or blunt tools lose their ability to cutting to the ground. Instead of effective cutting, blunt tools tend to compress and smear cohesive soils against the excavation face. Furthermore, as efficiency of tool protrusion decreases due to severe wear, the steel structure of the cutterhead begins to rub directly against the unexcavated ground. This generates excessive friction and heat, which alters the plasticity of the clayey materials and significantly exacerbates their adhesion to the metal surfaces. Consequently, the excavated soil fails to flow through the cutterhead openings into the chamber. This leads to the formation of "mud cakes" and increased torque, which disrupts the equilibrium between the excavation rate and muck discharge. In shallow soil cover, even minor fluctuations in face pressure or localised over-excavation caused by inefficient cutting can lead to immediate surface settlement or heave, posing a direct threat to the integrity of overlying utilities.

To mitigate these risks, the RTBM in the Stage 5B project was equipped with wear sensors embedded in the primary cutters, real-time torque and vibration analytics to detect early signs of deterioration, and a man-lock system to allow for manual inspection and cutter tool repair under compressed air if necessary.

3.3.3. Design of RTBM's Shield

In urban areas, the construction sites for launching and receiving shafts are often severely confined by limited spatial footprint and congested underground utilities. In the Stage 5B project, the fully assembled RTBM shield has a massive total weight of 540 tonnes and the machine size 10.8m(W) x 7.5m(H) x 6.4m(L), making the long-distance transportation of a single monolithic unit infeasible. To overcome these constraints, the RTBM shield was specially designed for manufacture and assembly. The machine was divided into six modular sections, this facilitated easier transportation and allowed for subsequent on-site assembly directly within the launching shaft (see Figures 16 and 17 in section 3.4.2, which illustrates modular units assembling on site). Finite element modeling (FEM) analysis as shown in Figure 12 was applied to take into consideration space constraints, ground conditions, and the RTBM assembly and dismantling sequences. This special design approach, coupled with specific operational provisions including strict logical sequencing for underground assembly and continuous dimensional verification, further reinforced the application viability of the technology in congested urban environments.

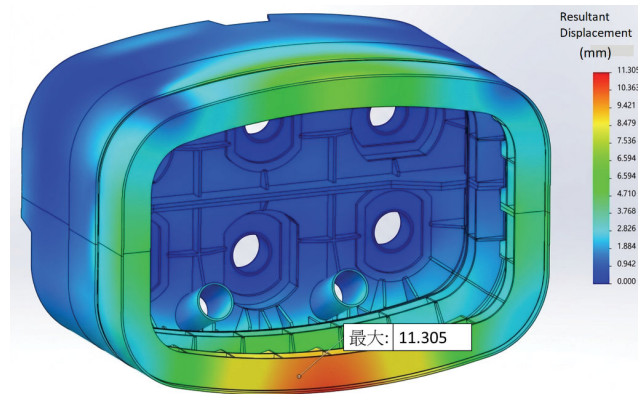


Figure 12 - FEM analysis for design of RTBM shield at Stage 5B

3.3.4. Thrust and Augmented Jack System

RTBM required greater thrust force than circular TBM due to higher friction during driving of RTBM and jacking of heavy-weighted tunnel segments. In the Stage 5B project, the thrust required was ranged between 20–30 MN based on ground conditions. However, to allow contingency or unexpected scenario, the designed thrust had capacity up to about 69MN. To further build in flexibility to cater for cobbles and hard materials, a front-side jacking system (Augmented Jack System) was incorporated as shown in Figure 13. This can also allow for more precise control on the tunnelling alignment. The steering system could maintain tunnel alignment with strict tolerances of cumulative deviation < 50 mm at any directions. Since the RTBM drive in the Stage 5B project was relatively short (~86 m long), intermediate jacking stations to manage thrust load and prevent overstressing the tunnel segments was not required.

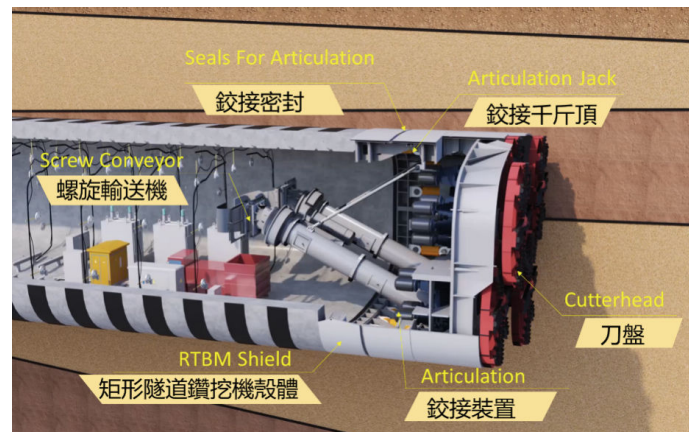


Figure 13 - Augmented Jack System

3.3.5. Man-lock and Compressed Air

RTBM cutterhead intervention was included in the design as a contingency plan such that in case of trapped boulders/rock fragments on the cutterhead, workers can access to the front face of the RTBM to carry out the necessary intervention works. Man-lock was sized to fit 3 workers and allow safe decompression. In the Stage 5B project, interventions will be conducted at 0.96 bar which was designed for soil stabilisation in front of cutterhead according to the GEO Report No. 298 Ground Control for EPB TBM Tunnelling. The man-lock was equipped with air storage tank, pressure stabilisation valves, emergency air supply, decompression control system and had been designed to meet the work safety requirements under CAP 59M Factories and Industrial Undertakings (Work in Compressed Air) Regulations.

3.4. RTBM Manufacture

The RTBM was manufactured in the factory in Shanghai by Shanghai Tunnel Engineering Co. Limited. The RTBM comprised different parts including cutterhead, cutterhead drive, shield, screw conveyor, working platform, auxiliary system, hydraulic system, control system, and power distribution system. Fabrication of the RTBM for the Stage 5B project took 8 months to complete. Figure 14 presented some photos taken during the RTBM's manufacturing process.

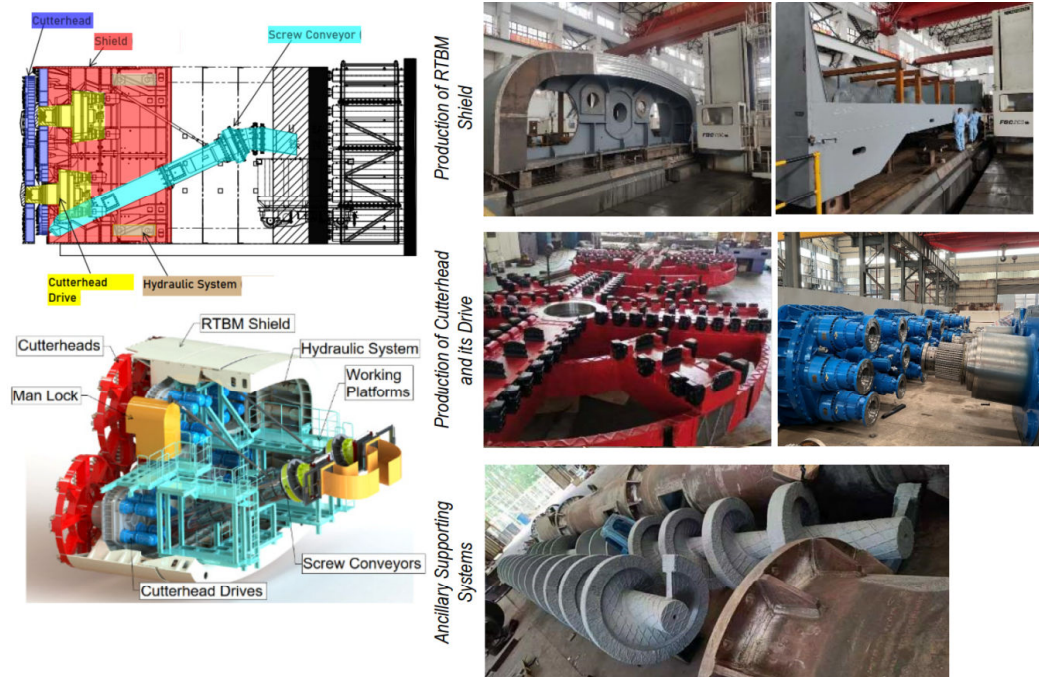


Figure 14 - Manufacture of RTBM

3.4.1. Factory Acceptance Test

The Factory Acceptance Test (FAT) was a critical stage ensuring that the RTBM delivered to site meets all functional, structural and safety requirements before use for tunnelling. The FAT provided the first full verification with the design against actual operation of the cutterhead drive, thrust cylinders, hydraulic circuits, face-pressure regulation, screw conveyor performance, and all monitoring and control systems as shown in Figure 15 below. During FAT, the cutterhead was rotated through its entire operating range to confirm torque stability, balance and vibration behaviour, while the hydraulic and steering systems underwent full-stroke and pressure testing to demonstrate operational responsiveness. The EPB chamber was pressurised to verify airtightness and the correct operation of conditioning injection lines. Tail shield sealing systems were inspected to ensure continuous protection during tunnelling, and electrical systems, including Programmable Logic Controllers, communication links, emergency stop functions, and Supervisory Control and Data Acquisition (SCADA) data transmission, were tested to confirm reliability.

All test results were documented comprehensively, with calibration certificates, inspection checklists, rectification records and updated as-built drawings forming part of the FAT dossier. This documentation provided a traceable record of the RTBM's conditions and readiness for deployment. It also established the baseline performance data for later comparison during site commissioning. The FAT should only be considered satisfactory when all performance indicators meet the specified requirements.



Figure 15 - RTBM Assembly for testing in fabrication yard before delivery to Hong Kong

3.4.2. Transportation and Assembly of RTBM

Transportation of the RTBM from the factory in Shanghai to the site in Hong Kong required careful planning and coordination for logistic arrangement via sea transportation in Figure 16 below, and also to tackle road width and headroom limitation underneath bridges via land transportation. The machine was delivered in modular units, which were wrapped with foam to protect against vibration, moisture penetration and accidental loads, with transportation scheduled during low-traffic hours after discussion and agreement with the Regional Management Office of the Hong Kong Police Force and the Transport Department.



Figure 16 - Delivery of RTBM to HKSAR by Sea and Land

Upon arrival, lifting operations were to be carried out with approved rigging plans to ensure safe unloading of the RTBM components into the launching shaft. Logical sequencing of RTBM's assembly was crucial: the main shield must first be positioned on temporary support beams or rails, followed by installation of the cutterhead, screw conveyor, drive systems and hydraulic circuits. Each stage of the erection process were checked for connection by welding or bolts. The cutterheads were installed and equipment inside the RTBM was being fixed as shown in the Figure 17.

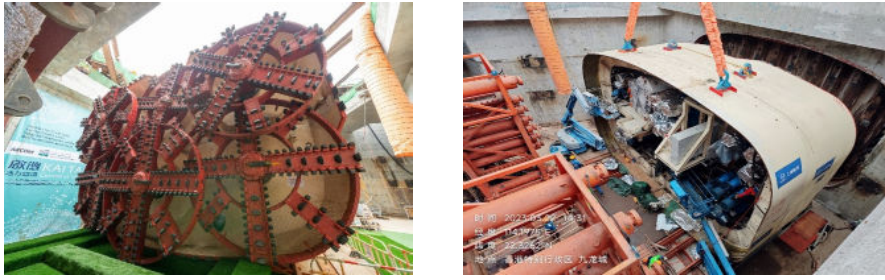


Figure 17 - Assembly of RTBM inside Launching Shaft

3.4.3. Site Acceptance Test

Once assembly was completed, the RTBM underwent pre-commissioning tests to confirm the proper functioning of all mechanical and electronic subsystems. These tests included idle cutterhead rotation, articulation movement, chamber pressure stabilisation, initial screw conveyor operation and low-pressure grout injection trials. The alignment of the RTBM was then calibrated using laser guidance to ensure compliance with the designed tunnel geometry. When all the RTBM components were ready and satisfactorily installed / setup, the RTBM was proceeded to the SAT.

The SAT served as the final validation that the RTBM had been properly assembled, calibrated and was ready to begin tunnelling operation. The SAT evaluated the machine under near-operational conditions, ensuring that the cutterhead, screw conveyor, hydraulic drives and articulation systems operated smoothly without abnormal noise, vibration or load fluctuations. The EPB pressure-support system demonstrated its ability to achieve stable pressure control suitable for tunnelling with shallow soil cover, while the data acquisition and monitoring systems were checked for accuracy, responsiveness and redundancy. The grouting system was tested through controlled injection sequences, confirming its capability to fill the annulus effectively.

Safety systems, including functional testing of emergency stop circuits, man-lock access, communication systems, compressed-air support and evacuation procedures, formed a major part of the SAT. The testing was conducted by the specialist of STEC and witnessed by resident site staff (RSS). The RTBM was not permitted to commission until all performance benchmarks were met, documentation was completed and the RTBM was certified as fit for tunnelling. The SAT established the operational baseline and ensured that the quality achieved during manufacturing and assembly was maintained during its use on site.

4. Construction Sequence

4.1. Ground Improvement

Ground improvement was a major step in the RTBM tunnelling works. In the Stage 5B project, the tunnel alignment passes through shallow, heterogeneous ground comprising FILL, ALL and locally CDG. The baseline soil parameters obtained showed low cohesion $c' = 0\text{--}4\text{ kPa}$, friction angle

$\phi' = 33^\circ$, and relatively low stiffness $E = 9,000\text{--}27,000\text{ kN/m}^2$, which together indicated a settlement-sensitive environment. Existing highways structures, underground utilities including stormwater drains, sewers, high voltage electric cables, and water trunk mains built in etc. crisscrossing the subway alignment imposed strict deformation limits, making ground stabilisation essential to safe tunnelling.

4.1.1. Ground Improvement before Launching of RTBM

Ground improvement was normally carried out prior to tunnelling so as to create a more uniform, predictable and therefore controllable excavation environment. As learnt from the previous Stage 3B project, the ground treatment in the Stage 5B project addressed three main issues:

- Soft FILL and loose ALL causing instability at the excavation face;
- Groundwater pathways contributing to potential inflow; and
- Sudden stiffness changes at FILL, ALL, CDG interfaces leading to settlement peaks

The ground improvement works aimed to strengthen weak or loose strata, fill potential voids, reduce permeability, stabilise the ground in front of the RTBM, and to provide a uniform reaction surface for face pressure control. Tube-A-Manchette (TAM) grouting was adopted in the Stage 5B project to form a highly stable soil block for the RTBM's initial drive from the launching shaft

4.1.2. Grouting Works during Driving of RTBM

When the RTBM was driven near or underneath the existing carriageway and various underground utilities, secondary grouting was performed to provide adaptive ground control. This process was implemented during or after tunnelling when unexpected voids were detected, settlement trends exceeded alert thresholds, or when annulus grouting was found to be insufficient in specific rings. Grout was injected via pre-installed pipes within the RTBM and radial grout ports in the tunnel segments. The volume of grout injected was calibrated based on real-time settlement monitoring, face pressure trends, and annulus filling ratios, with initial filling ratios increased when navigating soft strata.

Based on technical insights gained from the Stage 3B project, the alluvial stratum is sensitive to ground relaxation and immediate annulus support is required when penetrating through this stratum. In addition to the conventional grouting materials, Clay Shock was adopted for the Stage 5B project. Clay Shock (a proprietary, high-viscosity, and thixotropic grout) was specifically utilised to provide immediate support to the overcut area around the shield. This material increased the effective stiffness of the weak FILL and ALL strata and mitigated ground relaxation ahead of the face, thereby enhancing face stability and reducing surface deformation. The capitalisation of "Clay Shock" identified it as a specialised proprietary technical product with specific performance characteristics distinct from standard cementitious grouts.

4.2. Construction of Tunnel Segments

The tunnel segments were casted on site and the production process for these rectangular reinforced concrete tunnel segments was presented in Figure 18. The workflow included steel mould assembly, reinforcement cage installation, embedment fixing, concrete casting using controlled vibratory compaction, demoulding, quality inspection and storage. This industrialised construction process ensured high dimensional accuracy, structural integrity and consistent quality control.

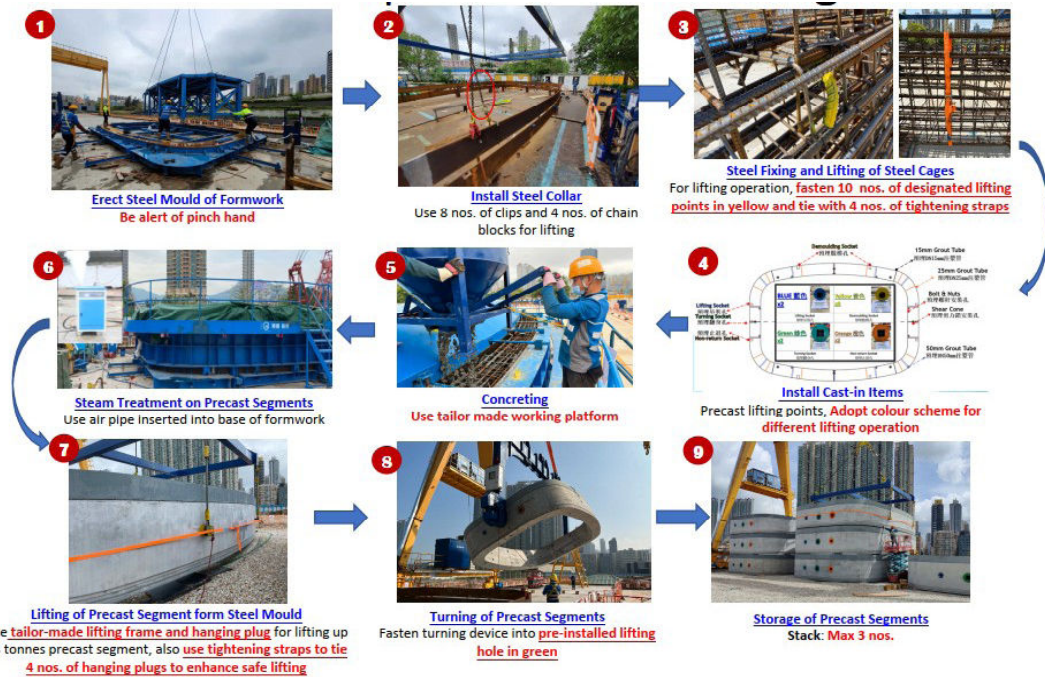


Figure 18 - Precast Fabrication Workflow for RTBM Rectangular Tunnel Segment

The Contractor developed tailor-made steel formwork which was equipped with working platform for concreting works. It could provide better quality assurance, enhanced construction rate and productivity, minimised noise and dust generation and had a better programme control. Each precast segment was about 78 tonnes. Instead of using traditional crawler crane for lifting operation, a gantry crane was erected for lifting of the precast concrete segments to enhance the stability of lifting operation, and extra safety devices were provided to control safety during the lifting operation.

Furthermore, a tailor-made turning device was designed and used for lifting and rotating the precast tunnel segment by remote controlled motor to eliminate complicated lifting operations or tendon lifting as detailed in section 4.3.4. This turning device was also used as lifting device for installation of precast tunnel segment into the launching shaft. This lifting operation did not involve direct labour input, i.e. remote control adopted, and it further enhanced lifting safety.

4.3. RTBM Operation Management and Control

4.3.1. Tunnel Construction Staff and Personnel

Effective RTBM operation for the Stage 5B project required a structured and experienced tunnelling team whom will be capable of managing the unique challenges during the tunnel drive at such shallow soil cover and mixed ground conditions, and to meet the strict deformation limits required by major utilities. The tunnelling team included RTBM operators, control room technicians, surveyors, mechanical and electrical fitters, grout plant operators, and safety personnel.

In the previous Stage 3B project, the variations in FILL / ALL strata causing the sudden torque fluctuations of the RTBM highlighted the need for a quicker interpretation of monitoring data and better coordination with the RTBM operator, timely adjustment of EPB conditioning and screw conveyor settings. Therefore, in the Stage 5B project, enhancement training for the tunnelling team was carried out as listed below:

- RTBM operators underwent enhanced training on managing oversized screw conveyors, which were introduced specifically in the Stage 5B project to cater for coarser gravels and to reduce pressure spikes.
- RTBM operators were trained in articulation control and shear-cone interface management, ensuring precise segment alignment.
- The communication protocols were strengthened:

Control room → Monitoring team → Grout station formed a closed-loop decision system, enabling immediate response to settlement trends.

Moreover, safety training was also conducted and focusing on shallow-overburden risk management, working near sensitive utilities, and operating the new segment turning device and heavy lifting system. The tunnelling team maintained a consistent, reliable, and uninterrupted operation of the RTBM tunnel drive.

4.3.2. RTBM Launching and Retrieval Requirements

Launching and retrieval of the RTBM were recognised as critical phases because the transition between shaft support and in-situ ground was identified as a risk zone. With reference to the experience gained from the Stage 3B project, minor face pressure fluctuations were observed during breakout and breakthrough of RTBM in the launching and retrieval shafts respectively. In view of this, the following improvements were made in the Stage 5B project:

- The oversized screw conveyor used in the Stage 5B project allowed smoother muck intake during early excavation, thus reducing the risk of under- or over-excavation at the launch face.
- Face pressure calibration curves were pre-developed using the Stage 3B operation data, ensuring stable pressure as the RTBM transitioned from the shaft support into heterogeneous FILL/ALL strata.
- Enhanced guidance and positioning systems were used to accommodate the larger and heavier tunnel segments in the Stage 5B project.
- Pressure reduction during breakthrough was conducted in finer increments, avoiding sudden decompression that could trigger face relaxation.
- Temporary support measures at the retrieval shaft were strengthened, taking into consideration of the higher total thrust force (36,000 kN) and larger excavation envelope in the Stage 5B project.
- Alignment tolerances were tightened. Together with the adoption of shear-cone for segment installation, the risk of mis-alignment in RTBM breakthrough was reduced to minimal.

The above measures collectively improved stability and reduced settlement risk during the tunnelling operation.

4.3.3. Face Pressure and Engineering Control Requirements

Maintaining correct face pressure during the RTBM drive was fundamental to prevent ground loss and to ensure safe tunnelling progression. In the Stage 3B project, it was revealed that torque and chamber pressure fluctuated when the RTBM drove through FILL / ALL interface, where cobbles in the soil matrix occasionally caused screw conveyor irregularities, and minor settlement peaks were detected. In view of this, the following enhancements were adopted in the Stage 5B project:

4.3.3.1. Oversized Screw Conveyor for Pressure Stability

The adoption of a larger screw conveyor significantly improved muck flow consistency, reducing pressure spikes and improving balance between intake and discharge.

4.3.3.2. Ground-Stiffness-Based Pressure Matrix

By reviewing settlement trends and soil stiffness values in the Stage 3B project, predefined pressure bands were implemented in the Stage 5B project:

Ground Layer	Behaviour in Stage 3B	Stage 5B Control Strategy
FILL	Highly unstable, sensitive to over-excavation	Higher support pressure + increased conditioning
ALL	Variable stiffness	Moderate, stabilised EPB pressure
CDG	Dense, stiff; uplift risk	Reduced pressure to prevent heave

4.3.3.3. Conditioning Optimisation

Soil conditioning including sodium silicate, polymer and bentonite were adjusted in real-time based on muck consistency. These adjustments were made via continuous feedback from cutterhead torque, screw conveyor current draw, and the chamber pressure gradient. The implementation of this closed-loop control approach resulted in a significant reduction in ground loss as compared with the performance achieved during the Stage 3B project.

4.3.3.4. Real-Time Monitoring Integration

Surface settlement monitoring data were directly linked to the EPB control system, enabling immediate operational adjustments. Any emerging upward settlement trend prompted an automatic review of key tunnelling parameters, including advance speed, cutterhead rotation speed (ranging from 0 to 2 rpm in the Stage 5B project), thrust distribution, and annulus grout pressure settings. This integrated real-time feedback mechanism as shown in Figure 19 enhanced the overall excavation stability and responsiveness.

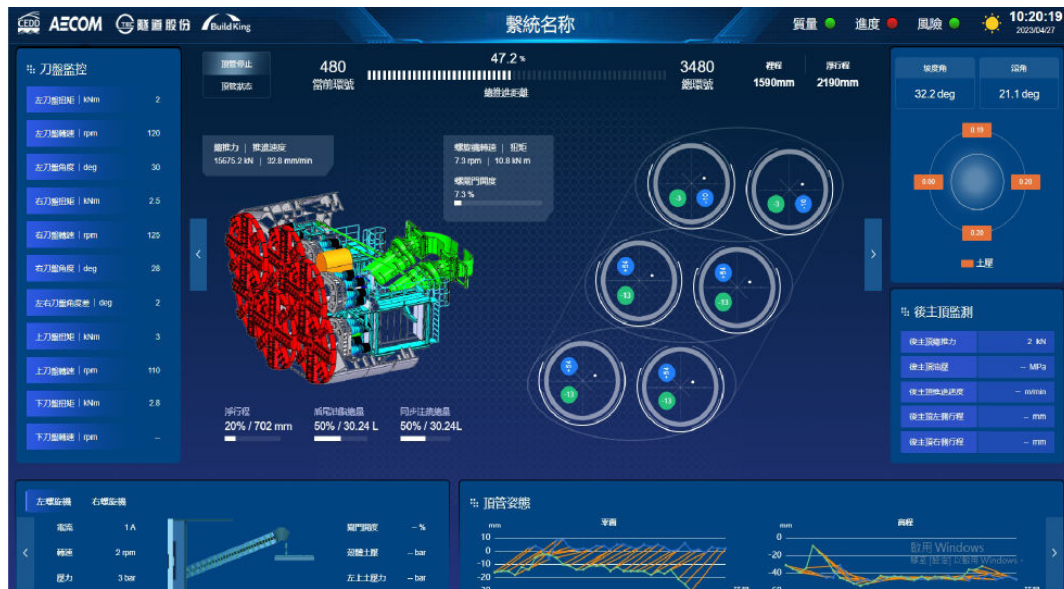


Figure 19 - Real-time Monitoring of Tunnel Alignment

4.3.4. Erection of Tunnel Segments

The tunnel segments were transported within the site by using remote controlled Self-Propelled Modular Transporter (SPMT), refer to Figure 20, which provide stable and safe condition for this heavy load of tunnel segments.



Figure 20 - Transport Tunnel Segment by using Remote Controlled SPMT and Lifting Operation by 115 Tonnes Gantry Crane

In the Stage 5B project, the following improvement measures were adopted as compared with the Stage 3B project:

- a. Shear Cones for Alignment Precision
Newly added shear cones ensured that each segment locked into the adjacent unit with minimal rotational or translational error
- b. New Segment Turning Device
A dedicated turning device was used to rotate heavy segments upright prior to installation, improving safety and accuracy as shown in Figure 21



Figure 21 - Newly developed Turning Device for Turning Tunnel Segments upright for Subsequent Installation into Launching Shaft

- c. High-Capacity Lifting and Transport Systems
 - Remote-controlled SPMT for transporting heavy components of RTBM and tunnel segments,
 - 115 tonnes gantry crane for segment lifting.

These systems were calibrated to reduce vibrations near the RTBM during erection.

- d. Improved Annulus Grouting
Enhanced grout pressure control and filling ratios directly improved the stability of lining support.

4.3.5. Transportation of Materials and Tunnel Segments within Tunnel

Material and segment transportation within the tunnel were carefully planned to avoid conflict with RTBM operation. Rail-mounted vehicle, locomotive, was used and with clear access paths established throughout the tunnelling operation. Spoil evacuation systems must be continuous to avoid backlog, and emergency access routes must remain unobstructed.

In the Stage 3B project, the cross-sectional area of the tunnel was relatively small (approximately one-quarter the area of the Stage 5B project). The restricted internal width and headroom meant that muck skips (for spoil removal) and segment transport trolleys could not bypass each other inside the tunnel. This physical "single-track" restriction dictated that spoil extraction / removal and segment could not be delivered simultaneously, leading to logistical conflicts and operational waiting times. In the Stage 5B project, leveraging the significantly larger tunnel cross-sectional area, these constraints were effectively resolved through the following measures:

- Upgraded Transport Equipment: Wider and more efficient transport system using rubber-tired carriers (e.g., remote-controlled SPMTs) that are not rigidly bound to tracks and are compatible with larger concrete segments.
- Cycle Synchronisation: Continuous coordination between RTBM advance cycles, segment delivery cycles and spoil removal cycles were implemented to maintain a seamless workflow.
- Digital Traffic Control: Integration of real-time tracking system was adopted to manage underground logistics and avoid traffic congestion near the critical articulation and ring-building zones.
- Optimised Spatial Planning: Unobstructed emergency egress routes were meticulously planned and implemented, effectively bypassing the heavy equipment.

These measures ensured uninterrupted RTBM tunnelling operation and reduced operational downtime.

4.4. Safety Requirement

Safe execution of RTBM works requires strict adherence to operational protocols governing cutterhead interventions, works underground and in compressed air, works in confined space, launching and retrieval procedures, and the protection of surrounding utilities. For the Stage 5B project, safety controls were substantially strengthened based on experience from the Stage 3B project, where shallow soil cover and mixed soil conditions created higher risks of face instability and ground relaxation.

4.4.1. Safety Management for Cutterhead and Chamber Interventions

Cutterhead and chamber interventions are considered to be the highest-risk activities in RTBM operation. The primary safety strategy for the Stage 5B project was aimed to minimise or entirely avoid the need for such intervention. This was done by fully understanding the soil behavior and the mixed soil strata conditions through experience gained from the Stage 3B project, and also improvement in the RTBM cutterhead design by increasing the number of scrapers as mentioned in section 3.3.1 above. Furthermore, the enhanced muck-handling capability of the oversized screw conveyor in the Stage 5B project significantly improved face stability and reduced cutterhead clogging. These proactive operational measures successfully eliminated the need for any cutterhead intervention during the entire RTBM drive in the Stage 5B project.

Although no intervention was ultimately required, a robust contingency procedure was established prior to RTBM's launching. Under this contingency plan, any necessary entry would only be carried out under fully controlled conditions. The RTBM was equipped with a certified man-lock and hyperbaric equipment, and protocols dictated that only medically certified and trained workers would be permitted to enter. A competent supervisor was standby to coordinate any potential intervention with real-time monitoring of chamber atmospheric conditions.

4.4.2. Compressed Air Work Safety

Compressed air operations were planned in accordance with statutory hyperbaric safety requirements, and only to be carried out on site if found necessary during tunnelling works. Workers underwent medical assessment and were trained in decompression procedures, exposure limits and emergency response protocols. A man-lock, i.e. compression and decompression chamber remained available on the site at all times. In the Stage 5B project, an improved risk-based intervention assessment was implemented, based on experience gained from the Stage 3B project. The assessment evaluated the parameters like ground type, torque variability and expected cutterhead loadings and assessed the probability of requiring compressed-air access. This reduced unnecessary hyperbaric entries and ensured that only essential interventions were executed, thereby minimised exposure to hyperbaric risks.

4.4.3. Confined Space and Underground Work Safety

RTBM tunnelling constituted a highly restricted environment requiring continuous atmospheric monitoring and strict personnel access control according to the Code of Practice for Safety and Health at Works in Confined Spaces issued by Labour Department. Entry into high-risk confined spaces, Permit-to-Work system and rigorous tag-in/tagout procedures for any personnel entering confined space were enforced. Air quality within the tunnel and the RTBM structure was continuously monitored for oxygen levels, carbon dioxide, methane, and toxic vapour. In addition, tunnel access was separately managed by a smart tag-in/tag-out RFID system to track the exact number and location of workers working underground at all times. These items of safety equipment were presented in Figure 23 below.

4.4.4. Safety Controls During Launching and Retrieval

The launching and retrieval of RTBM were identified as critical activities requiring high levels of engineering and operational coordination. The RTBM break-in was illustrated in Figure 22 below. The Stage 5B project adopted a refined pressure-transition procedure that incorporated incremental face-pressure adjustment, based on the pressure-instability patterns observed in the Stage 3B project. Deformation of tunnel segments were continuously tracked using automated total stations measuring fixed convergence targets in real time as discussed in section 5.3, and ground surface settlement and movement were monitored at least twice daily, allowing immediate response to early signs of relaxation. Alignment tolerances were also tightened to ensure that the RTBM reached the retrieval shaft in a more accurate position and orientation, avoiding the eccentric breakout conditions. These stepped-up control measures significantly reduced the likelihood of face collapse, ingress of loose materials or excessive ground deformation during the RTBM breakthrough into the retrieval shaft.

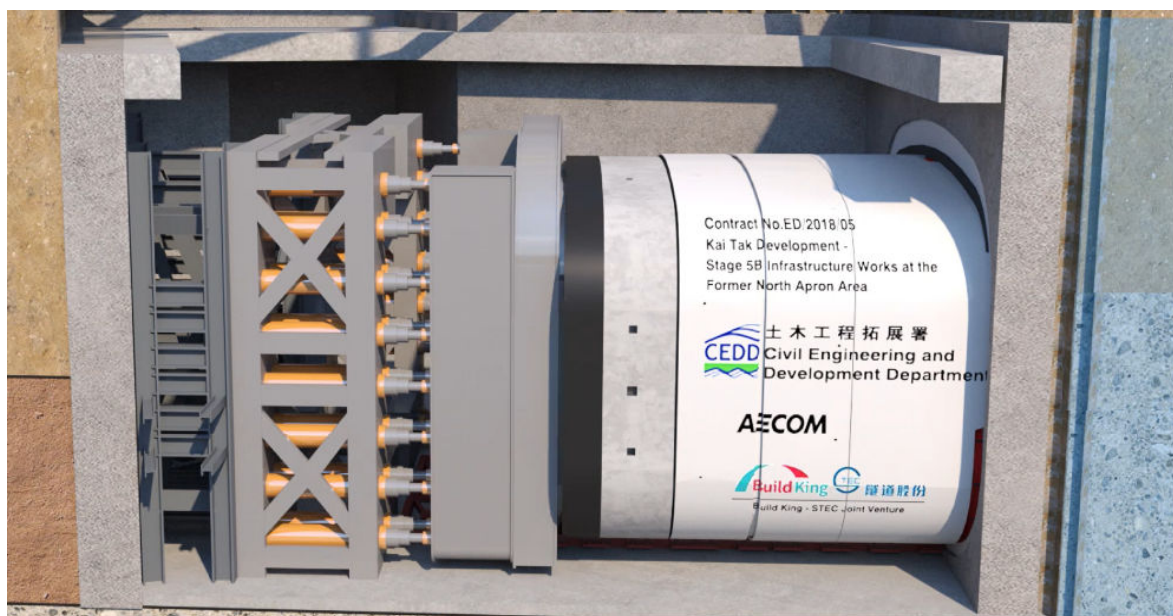


Figure 22 - RTBM Break-in

4.4.5. Smart Site Safety Devices

Smart site safety devices were also adopted, including Artificial Intelligence (AI) Cameras for monitoring the danger zone of lifting operation at launching shaft, monitoring the Personal Protective Equipment at entry of confined space, 24-hour continuous gas monitoring inside Confined Space, face recognition for entry into Confined Space and implementation of tag system for access control to tunnel, refer to Figure 23. These monitoring data were all displayed in a centralised management platform for instant monitoring.



Figure 23 - Smart Site Safety Devices

4.4.6. Fire Safety and Emergency Preparedness

Fire safety for tunnelling operation includes the provision of flame-retardant cabling, multi-point fire extinguishers, hydrant systems, and refuge chambers with independent air supply. Emergency communication systems were enhanced with redundant wired and wireless channels to maintain connectivity in the event of equipment failure. Emergency drills were conducted regularly to simulate fire, flooding and entrapment scenarios, ensuring that all personnel could respond effectively under emergency conditions.

The 86-m long pedestrian subway in the Stage 5B project was constructed across PERE and Sa Po Road connecting Kowloon City to KTD area. Prior to the commencement of the tunnelling operation, a Crisis Management Plan (CMP) was established. The CMP outlined the procedures for handling and managing crises by the client's office, the RSS and the contractor's team. Incident reporting and updating, formulation of line-to-take, and resource management for handling unforeseen incidents were addressed in the CMP. Under this CMP, TTA schemes in different scenarios (total 7 nos.) were developed to cater for emergency road closures during subway construction. These schemes were discussed in the Traffic Management and Liaison Group (TMLG) meetings and further revised to address comments by the TMLG members. Within a total of 5 months, approval from TMLG members were successfully received.

4.5. Risk Assessment

The risk assessment for the Stage 5B project expanded upon the findings from Stage 3B project, focusing on a critical technical challenge: the RTBM used in the Stage 5B project features a cross-sectional area significantly larger than that of the Stage 3B project. This significantly increased the excavation face and the machine will be exposed to a higher degree of geological complexity and mixed-ground conditions. To mitigate “Geological and Excavation Risks”, comprehensive Ground Investigations (GI) were conducted to accurately identify and pre-classify specific high-risk zones along the tunnel alignment, particularly chainages containing cobbles and corestones, and the RTBM was upgraded with an oversized screw conveyor accordingly. This equipment upgrade, combined with refined soil conditioning parameters (i.e., the optimised injection of sodium silicate, polymers or bentonite into the cutterhead to improve muck rheology and maintain face pressure), stabilised the tunnel face and ensured consistent muck flow, significantly reducing the likelihood of blockages or ground loss.

Regarding “Ground Deformation and Utility Risks”, settlement concerns were elevated in view of the shallow soil cover condition and the proximity to critical underground utilities. These included the 400 kV/132 kV high-voltage cables located within the immediate zone of influence, as well as the highly sensitive, aged water trunk mains built in the 1960s. To manage the risks, the project adopted a dynamic, observational approach to RTBM control. Initially, the baseline parameters for the settlement model and monitoring plan were established through a comprehensive analysis of the specific site conditions and the existing geological data. However, as the RTBM operated, it was critical not to solely rely on these static initial parameters. Instead, predictive settlement envelopes were continuously recalibrated using the latest site monitoring data. Monitoring readings from the surface and adjacent underground utilities were fed directly into a real-time feedback loop in the operator cabin as shown in Figure 24. This live data allowed the tunnelling team to immediately modify and optimise active RTBM operational parameters, such as face pressure, thrust force, or grouting volume, directly response to the actual soil behavior. Coupled with this adaptive control strategy, “Clay-Shock” as a ground treatment was adopted at sensitive locations, halving the predicted settlement compared with untreated areas. Furthermore, strain and deformation triggers were linked directly to tunnelling operations via a real-time feedback loop to the operator cabin, enabling immediate adjustments to face pressure or thrust force.



Figure 24 - Central Monitoring Station (left) and Operator Cabin in Site Control Room (right)

To address “Hydraulic and Annulus Grouting Risks”, the Stage 5B project introduced stricter pressure and time controls for annulus grouting to prevent void formation and water ingress in permeable reclaimed ground. Precise steering was implemented via articulation jacks, and continuously monitoring of the injection volumes and tail-skin back-pressures. These measures further enhanced support around the tunnel segments. For “Machine Behaviour and Alignment Risks”, torque and chamber-pressure thresholds were calibrated based on previous variance patterns recorded during the Stage 3B project. This empirical reference was highly relevant as both projects share identical mixed-face geologies (FILL and ALL interfaces), allowing for the early detection of adverse conditions. The introduction of shear cones and closer monitoring of shield articulation ensured precise segment alignment and geometric accuracy under asymmetric ground loads.

Finally, “Personnel and Hyperbaric Work Risks” were significantly mitigated through the safety measures mentioned in section 4.4 above and increased mucking efficiency and soil stability. Therefore, the compressed-air intervention was not required, and it effectively eliminated personnel exposure to hyperbaric and confined-space hazards.

In conclusion, the strategic refinements implemented in the Stage 5B project, from advanced ground treatment to mechanical upgrade on the RTBM demonstrated a proactive shift from reactive mitigation to predictive risk management. By systematically applying lessons learnt from the Stage 3B project, the project successfully navigated extreme technical constraints and protected utility infrastructure while simultaneously enhancing personnel safety through reduced hyperbaric exposure.

4.6. Environmental Permits and Controls

Environmental control measures must be strictly implemented to manage noise, vibration, dust, slurry disposal, and wastewater generated from the RTBM tunnelling operations. Real-time settlement and vibration monitoring must operate throughout the RTBM drive to prevent adverse impacts on the surrounding sensitive receivers. All works must strictly comply with statutory environmental legislation in Hong Kong, including obtaining and adhering to the relevant Environmental Permits (EP), Construction Noise Permits (CNP) for any restricted-hour operations, and effluent discharge licenses for wastewater and slurry management.

5. Monitoring System

Supervision and monitoring in the Stage 5B project were formulated based on the lessons learnt from the Stage 3B project, where the tunnel alignment was also subject to shallow soil cover, within reclaimed fill, and with the presence of major utilities in vicinity. Rather than applying a generic monitoring protocol, the monitoring system in the Stage 5B project adopted enhanced instrumentation including surface settlement markers and utility monitoring points at significantly closer intervals over the critical tunnel footprint, and real-time feedback loops to machine control, where surface monitoring data was instantly relayed to the operator cabin to actively adjust EPB targets, thrust forces, and annulus grouting pressures. These measures allowed the tunnel excavation to be continuously carried out without affecting the numerous major utilities in vicinity, including high voltage electric cables, aged water trunk mains which were built in 1960s, and also without affecting the heavy traffic route of PERE above the tunnel.

5.1. Ground Surface and Utility Settlement Monitoring

The monitoring design for the Stage 5B project had taken into consideration the high geotechnical risks observed in the Stage 3B project, in particular the settlement trends within the FILL and ALL strata. Monitoring was therefore configured to provide faster detection of any movement by increasing the surveying frequency to 6-hour intervals during critical excavation phases and direct input monitoring result to RTBM control platform, enabling the immediate adjustment of soil conditioning injection ratios and screw conveyor discharge volumes to halt any adverse settlement trends before they exceeded allowable limits.

5.1.1. Ground Settlement Monitoring

Surface settlement monitoring in the Stage 5B project, as shown in Figure 25, was intensified as compared with the Stage 3B project due to the reduced ground, the presence of aged and large sized utilities directly above the tunnel, and greater excavation face of the tunnel construction. Settlement arrays were installed at closer spacing, and the monitoring frequency during critical excavation phases was increased to 6-hour intervals, providing a faster response time against settlement observed during the RTBM drive.

This enhanced monitoring allowed immediate change, such as increasing soil conditioning, or higher annulus grout pressure, to be enacted. These active interventions effectively minimised ground volume loss, thereby reducing the maximum depth and width of the surface settlement troughs, i.e., the downward sagging of the ground surface, along the tunnel alignment.

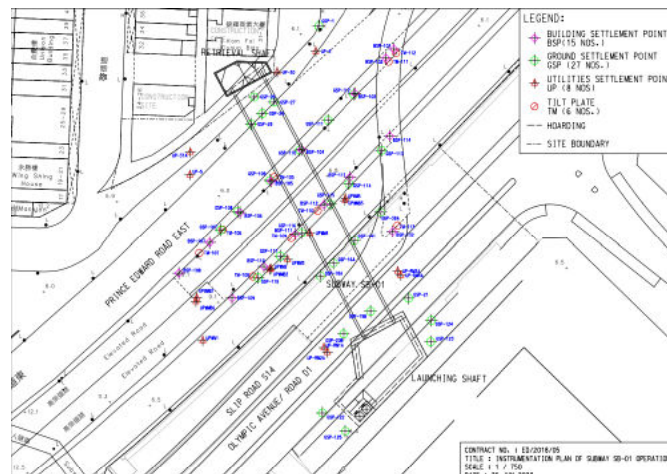


Figure 25 - Monitoring Plan

Action plan for triggering Alert, Action and Alarm levels, as shown in Figure 26, was established prior to RTBM driving.

Action Plan for Alert, Action and Alarm Response Values		
Alert	Action	Alarm
-Inform the Supervisor -Inform the Designer -Inform Management Department, CEDD -Inform external government bodies (i.e. TD, HyD, GEO, etc.) by the Supervisor if necessary -Close monitor and detect whether the alert level was reached within 24hrs -Carry out visual inspection of the surface ground condition and affected structures to review the cause of effect - Increase frequency of monitoring	-Inform the Supervisor -Inform the Designer -Inform Management Department, CEDD -Inform external government bodies (i.e. TD, HyD, GEO, etc.) by the Supervisor if necessary -In front of RTBM: Earth pressure, attitude, RTBM position and rotation angle to be adjusted -Above the Subway SB-01: Inject clay shock with yellow mud thick slurry, and strengthen reducing bentonite slurry grouting -Review the causes of continuing settlement -Inject the bentonite slurry to prevent the continuing settlement -Increase the face pressure to the designed upper bound level during driving -Review the settlement markers response and setup at least 2 additional settlement markers in the affected area to enhance the monitoring work -Increase the visual inspection to thrice a day -Arrange a trained worker stay at the ground level of cutter head position to keep monitoring the ground condition -Prepare and submit remedial proposal to the Supervisor -Design assumption should be review by designers and ICE if any variations arise, the updated design should be submitted to the Supervisor for acceptance	-Suspend RTBM driving -Inform the Supervisor -Inform the Designer -Inform Management Department, CEDD -Inform external government bodies (i.e. TD, HyD, GEO, etc.) by the Supervisor if necessary -Immediate remedial works should be proposed by the Contractor and specified on site -Submit remedial proposal to the Supervisor -Inject the anti-settlement soil conditioner to the settlement location to support the soil and backfill the over excavation/void to prevent continual settlement -Joint inspection of the affected area and the instrumentation points to investigate whether the settlement was caused by any external works or the sudden change of surface ground environment -Meet with the main contractor. Discuss and review the causes and measures of the settlement -Excavation chamber should be backfilled to safe level determined by Designer and Supervisor -No works shall be resumed without the acceptance of the Supervisor

Figure 26 - Action Plan

5.1.2. Machine-based Monitoring and Operational Feedback

Machine-based monitoring in the Stage 5B project was upgraded to integrate data acquisition for new equipment with higher capabilities. Specifically, this monitoring upgrade included the real-time tracking of discharge volumes and pressure gradients for the newly installed oversized screw conveyor, as well as the precise logging of injection flow rates and back-pressures for the enhanced annulus grouting control system. Cutterhead torque, chamber pressure, and screw-conveyor load were monitored with higher-frequency sampling.

Key improvements in the Stage 5B project included:

- Alert thresholds for chamber pressure and cutterhead torque were recalibrated based on the fluctuation patterns recorded during the Stage 3B project.
- Real-time machine data were cross-compared with settlement to detect correlations between excavation instability and ground movement.
- Operational feedback loops were shortened so that any drops below the target EPB limits or sudden torque spikes triggered immediate adjustments in face pressure, thrust force, soil conditioning ratios (e.g., sodium silicate, polymer or bentonite) injection rates, or grout injection volume.

This closed-loop monitoring approach resulted in more stable excavation conditions than those achieved in the Stage 3B project.

5.1.3. Visualisation and Data Management System

During the RTBM's drive in the Stage 5B project, real-time monitoring as shown in Figure 27 was established. It included digital monitoring for i) cutterhead torque, power and speed; ii) chamber pressure; iii) the pressure difference along the screw conveyor casing, which tracks the gradual dissipation of earth pressure from the pressurized soil chamber down to the atmospheric discharge gate, ensuring the formation of a safe soil plug; iv) shield attitude (pitch, roll, yaw); v) hydraulic system pressures; vi) grouting performance; and vii) external ground movement sensors (integrating automated surface settlement data straight onto the RTBM operator's dashboard for immediate correlation with excavation parameters). This system successfully detected abnormal torque spikes indicating entry into ALL stratum, enabling early adjustment of conditioning parameters. Data was recorded at intervals not exceeding 1 second.



Figure 27 - Computerised Real-Time Monitoring and Control System

5.2. Tunnel survey requirements

Based on lessons learned from the Stage 3B project, where cumulative deviation of tunnel alignment occurred at FILL and ALL interface due to asymmetric geological loading, survey control was strengthened in the Stage 5B project. The survey regime incorporated more frequent verification intervals to enable quicker operational feedback to ensure the tunnel alignment remained within stricter tolerances.

5.2.1. Alignment Control and Guidance System

The alignment control system in the Stage 5B project as shown in Figure 28 incorporated enhanced guidance accuracy and more responsive correction procedures based on lessons learnt from the Stage 3B project.

Key improvements in the Stage 5B project included:

- Refined laser guidance system with greater stability against vibration and dust disturbance, addressing issues experienced in the Stage 3B project.
- More frequent manual survey checks (every 1 to 2 precast tunnel segments in critical zones), allowing earlier detection of pitch and yaw drifts
- Establishment of additional in-shaft reference brackets and intermediate survey control points (e.g. relay prisms) along the tunnel intrados. This provided critical line-of-sight redundancy and continuous positional verification, mitigating the risk of laser blockages or signal loss that occasionally compromised the single-source setup in the Stage 3B project.
- Faster articulation adjustment workflow, enabling the tunnelling team to correct deviation in tunnel alignment before the deviation accumulated.

These measures significantly reduced the need for major steering corrections that were required in the Stage 3B project.

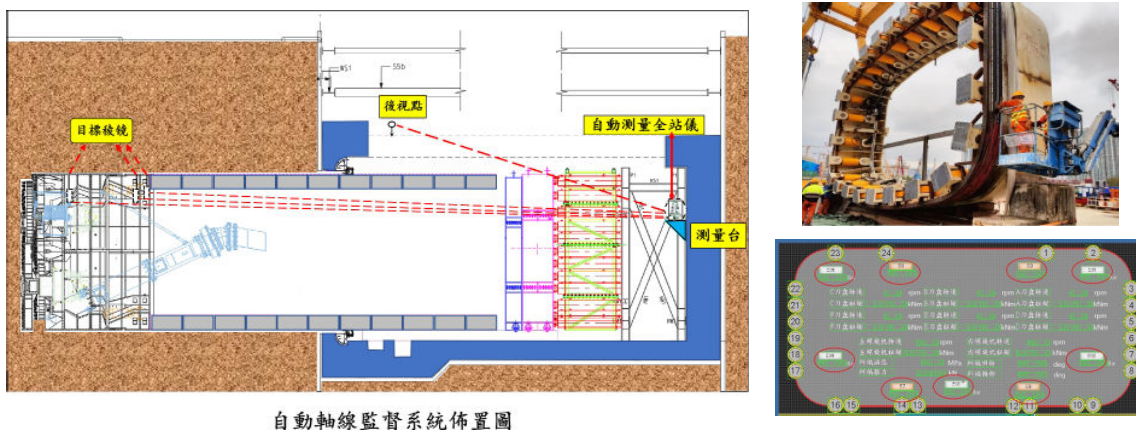


Figure 28 - Alignment Monitoring System

5.2.2. Tunnel Segments Geometry and Installation Survey

The tunnel segments geometry control for the Stage 5B project was enhanced based on the experience gained during segment installation in the Stage 3B project. In the Stage 3B project, minor roll deviations and uneven joint gaps between consecutive rectangular tunnel segments were occasionally observed when the RTBM passed through zones of asymmetric loading, where one side of the segment experienced higher ground pressure than the other. These small geometric distortions, although within structural limits, had the potential to accumulate and exceed the allowable final construction tolerances if not addressed at earlier during the segment installation.

In response, the Stage 5B project implemented stringent acceptance criteria for precast segment alignment, spatial orientation, the closure gap between tunnel segments and annulus clearance. Enhanced survey checks were carried out immediately after each installation of tunnel segment using a combination of laser plumb-line systems and total-station measurements. Uniformity of annulus grout filling was also subjected to closer inspection. Experience from the Stage 3B project heavily underscored that meticulous and complete infilling of the tail void is critical as a proactive measure to prevent any risk of long-term ground settlement or localised ground deformation. The improved survey and verification process ensured that each precast tunnel segments conformed to its design geometry, providing consistent structural performance along the full tunnel alignment.

5.2.3. Settlement, Convergence and Structural Deformation Surveying

The deformation surveying for the Stage 5B project was enhanced to provide a quicker and faster response to ground settlement and movement, especially when the RTBM approached the FILL and ALL interfaces.

The enhancements under the Stage 5B project included :

- Higher-frequency settlement surveys above the PERE. To avoid disrupting this major heavy traffic sensitive carriageway, installation of permanent automated monitoring instruments on the road surface was prohibited. Instead, manual surveying at half-daily intervals was being carried out for monitoring settlement and movement on road pavement.
- More frequent tunnel convergence checks using fixed tunnel segments' survey targets to detect distortion earlier.
- Expanded crack and structural movement monitoring at adjacent highways structure that fall within the theoretical zone of influence. This was implemented as a proactive precaution, recognising that the significantly larger excavation profile of the Stage 5B RTBM inherently alters the surrounding stress distribution compared with the Stage 3B project.

These direct surveying methods served as a robust secondary verification to the automated instrumentation, triggering timely operational interventions, such as EPB adjustment or supplemental grouting if found necessary.

6. Conclusion

6.1. Core Advantages and Technical Effectiveness

The implementation of RTBM has proven highly effective for constructing pedestrian subways and other underground structures such as vehicular tunnels and underpasses, in particular in urban areas with heavy traffic flow, congested and aged underground utilities and shallow soil cover. The excavation process is well controlled and continuous support can be provided to the excavation face. The excavated profile can be precise, which minimises the overcut annulus between the surrounding ground and the precast segments. This can significantly reduce the risk of ground loss and ground settlement. Compared with traditional cut-and-cover or mined excavation, RTBM delivers enhanced safety (by isolating workers from unlined excavation faces and eliminating the need for deep, open trenches), reduced surface disruption, and improved construction predictability (achieved through consistent mechanised advance rates and standardised precast segment assembly), making it a highly suitable method for tunnelling works in congested urban area like Hong Kong. Key technical advantages include:

- **Optimal Spatial Efficiency:** The RTBM directly forms a rectangular profile that perfectly matches the functional envelope of pedestrian walkways, eliminating the unused corner spaces inherent in circular TBM and substantially reducing secondary structural works.
- **Customisation for Confined Sites:** Utilising a DfMA approach, the RTBM shield can be separated into compartments for safe underground assembly, perfectly addressing the spatial constraints when constructing the launching shaft in congested area.

6.2. Project Evolution and Engineering Experience

Valuable experience was gained from the previous Stage 3B project, which marked the first successful application of RTBM in Hong Kong. It demonstrated the successful tunnel construction by RTBM under severe limitations to traditional method of constructions, i.e. cut-and-cover or mined excavation methods, where the construction was to be carried out under shallow soil cover, in proximity to congested underground conditions and at areas of traffic-sensitive conditions. These traditional construction methods inherently involve prolonged construction durations, extensive temporary traffic management (TTM), greater risks of ground settlement, and severe interface issues with existing utilities. In contrast, the RTBM method eliminated the need for massive temporary works, minimised direct impacts to utilities, and provided superior ground settlement and movement control.

Building on this foundation, the Stage 5B project adopted a significantly larger RTBM, featuring four times the cross-sectional area of the Stage 3B machine. To safely manage this increased scale, the RTBM system was further improved with an oversized screw conveyor for better muck handling, higher-frequency automated machine monitoring, and refined DfMA assembly protocols. This successful evolution, and the resulting improvements in efficiency, safety, and settlement performance, firmly demonstrated RTBM's superiority for constructing large-span pedestrian subways in highly constrained urban environments, particularly where shallow soil cover and congested utility networks strictly prohibit traditional open-cut excavations.

6.3. Key Lessons Learnt and Operational Enhancements

Several key lessons were emerged from the RTBM construction works carried out in the KTD projects:

- **Advanced Ground Investigation:** Early and accurate ground investigation, enhanced by geophysical surveys, was essential for determining appropriate face pressure, soil conditioning strategies and identify any underground obstructions, such as large size boulders or uncharted objects which will affect the cutterhead design.
- **Predictive Digital Monitoring:** The real-time integration of machine data (e.g., torque, chamber pressure) with high-frequency surface settlement monitoring drastically improved the ability to detect anomalies and react promptly.
- **Skilled Execution and Smart Safety:** Effective management of segment installation, synchronous grouting, and machine articulation requires skilled personnel and continuous supervision. The integration of Smart Site Safety Devices (e.g., AI cameras, remote-controlled SPMTs) further mitigated risks associated with heavy lifting and confined spaces.
- **Shaft Logistics:** The importance of meticulous design of launching and retrieval shafts was strongly reinforced, especially given the restricted / confined area for shaft construction in urban congested areas like the HKSAR and also the complex lifting arrangements.

6.4. Future Prospects and Industry Foundation

The successful adoption of RTBM provides a strong technical foundation for mechanical rectangular tunnelling in future infrastructure developments. RTBM offers a low-surface-impact, structurally robust, and highly safe alternative to traditional open-cut methods for constructing pedestrian subways, utility tunnels, and underground structures with shallow soil cover. The proven capability of the RTBM adopted in the Stage 5B project which a significantly larger excavation face had been carried out and the RTBM had been able to navigate complex mixed-face geologies further demonstrates the immense scalability and potential of this method. Ultimately, the empirical lessons learnt from the two subways construction projects in the KTD shape clearer, systematised technical frameworks for the design, construction, monitoring, and risk management of RTBM construction; firmly supporting and accelerating the wider industry adoption of this technology.

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