Underground Development - Pipe Curtain with Jack-in-place Rectangular Tunnel Boring Machine Technology

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ABSTRACT

With the recent successful application of Rectangular Tunnel Boring Machine (RTBM) Jack-in place technology in Hong Kong, more interest is put into its wider use. However, the application of RTBM is restrained by geological limitations, such as shallow overburden depth, limited span depth ratio of the tunnel (< 2), etc. Advanced underground construction technology – the adoption of systematic pipe curtain with Jack-in place RTBM methodology- was introduced recently in China and Overseas to construct underground railway tunnels, stations, pedestrian subways, and underpass in challenging congested urban areas. This advanced methodology focuses on underground structures construction in which stringent settlement control with shallow overburden cover is required. It also possesses the flexibility to adapt to different sizes of cross-sections, which makes wide span (>20m) underground structures can be constructed by the trenchless method. Given the future of Hong Kong infrastructure development, this paper is aimed to explore the potential for developing underground space based on this advanced solution to resolving problems in an old and congested urban area. Taking past successful project experiences in Mainland China as examples, this paper has discussed the geological requirements, construction method, sequence, ground settlement performance, etc. It also provides consideration that should be aware of the adoption of technology in typical Hong Kong geological conditions. The RTBM technology offers a new solution to the infrastructure development projects in Hong Kong with better buildability, safety and productivity.

Keywords: Underground Development, RTBM, Pipe Curtain Method

1 Introduction

With the continuous urban development, a large number of existing facilities (roads, railways, municipal pipelines, etc.), three-dimensional intersection projects and underground passage projects have emerged. These projects can resolve the traffic bottlenecks formed by the construction of existing facilities, which are of great significance for alleviating the problem of regional traffic congestion and can substantially improve the travel efficiency of the entire transportation network. However, the surrounding environment of such projects is complex, often characterised by heavy regional traffic, limited construction land and underground space availability. With the increasing public engagement in modern society, when constructing the underpass structures under the existing facilities, the public demands stringent requirements on construction safety and less impact on the surrounding environment, which makes the trenchless technology face high challenges.

The successful completion of a subway structure using the jack-in-place RTBM technology has proved

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that mechanical construction methodology can effectively fulfil safety and environmental concerns. This paper is aimed to explore another dimension of this automated technology by discussing the limitation of the technology itself, introducing an advanced approach, a combination of systematic pipe curtain technology together with RTBM to deal with the more complex underground condition. Case studies for projects in Mainland China have demonstrated the potential for broader application of RTBM methodology to achieve higher productivity, better safety and environmental control in a construction project that benefits future development in Hong Kong.

2 Limitation of Jack-in-place RTBM Methodology

auxiliary	Trenchless methodology		
	Jack-in-place Segment RTBM	**New Austrian Tunnelling Method (NATM)**	**Large dia. TBM**
Cross-section span	Width W ≤ 12m	Unlimited in theory	Dia. *D* ≤ 17m
Shallowest overburden	1.0 *D*	3 m	1.0 *D*
Cross-section utilization	★★★★	★★★★	★★
Flexibility of cross-section	★★★	★★★★★	★★
Disturbance to ground	★★★	★★	★★★★
Site utilisation	Less demanding	Less demanding	Demanding
Safety	★★★★	★★	★★★★
Construction cost	★★★★	★★★★★	★★★★
Construction period	Short for <200m	Long	Short for long tunnel

Figure 1: Comparison of common trenchless methodology

Figure 1 compares three trenchless technologies in terms of several important elements for a construction project. The advantages of using the jack-in-place segment RTBM method to construct underground structures are significant, especially in short distances (< 200m) in subway structures construction; its effectiveness is outstanding. In mainland China, the technology has been applied in other scenarios, such as vehicular underpass, underground podium construction, etc. In a recent project in HK using this technology, the internal structure envelope formed by the machine is 9m in width, and 5m in height (on average), which has demonstrated its potential usage in other underground structures construction. However, this leads to two major limitations. The first is the overburden depth. In general, 1.0D overburden depth is required when designing using the jack-in-place segment RBM structure, which implies a deep structure invert level for the pedestrian subway or a longer slip road for the vehicular underpass. The second one is the span width of the structure to be built; due to the potential hazard of the “Segment-crown soil carrying effect” (a phenomenon observed in jack-in-place segment RTBM technology that can cause severe ground structure disturbance), the span width of the machine is limited to 12m. Those two constraints limit the technology usage flexibility and its potential to apply in structures where a wider cross-section is needed.

Advanced technology is introduced to overcome these two shortfalls, known as the systematic pipe-curtain method. In simple terms, this is an upgraded version of the pipe roofing method. The combination of systematic pipe-curtain with jack-in-place segment RTBM method has the characteristics of minimum environmental impact, strong soil adaptability, and flexible cross-section layout. By adjusting the layout of the pipe curtain and the prefabrication of the segment lining components, tunnel or subway structures passing through complex existing structures or utilities is feasible and has very high cost-effectiveness for short-distance crossing in congested urban areas.

3 Characteristics of the Pipe Curtain Construction Method

The pipe curtain with jack-in-place segment RTBM construction method refers to the methodology of using the rectangular TBM drilling through an underground horizontal section which is protected by the formed pipe curtain to construct the underground structure. The pipe curtains are connected by standard male and female sockets with grouting, which can create a watertight curtain closure. It is different from the typical interlocking pipe pile in which special design steel pipes connect each other without any protruding part.

Special pipe locking design

The high precision hidden type pipe interlocking design effectively controls the alignment of the pipes installation

Figure 2: Hidden type interlocking pipeline arrangement

Figure 2 shows the typical arrangement of the unique design pipelines, which are installed by a mini-pipe jacking machine with laser target alignment control. The machine is equipped with a multi-level articulation system to control the pipe installation, as shown in Figure 3. With the systematic interlocking pipe arrangement, the technology can ensure the pipe curtain is formed precisely and with minimum impact on the surrounding environment.

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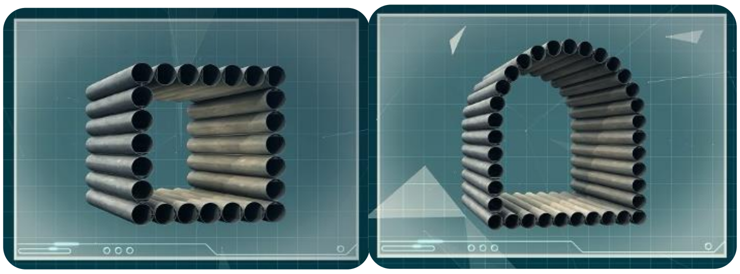
Figure 3: Mini-pipe jacking machine for pipe installation

The pipe curtain can be formed in a different shape to suit the structure requirement. Once these pipelines protection is formed, the jack-in place segments by the RTBM can be installed within this protected zone.



The pipe curtain effectively controls the impact on the ground caused by the segment jacking operation. Combining two technologies, five advantages for underground structure construction can be achieved, as shown in Figure 4.

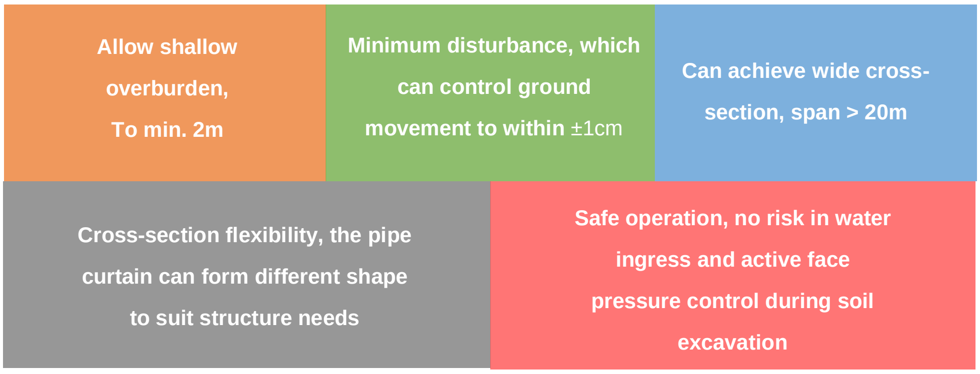
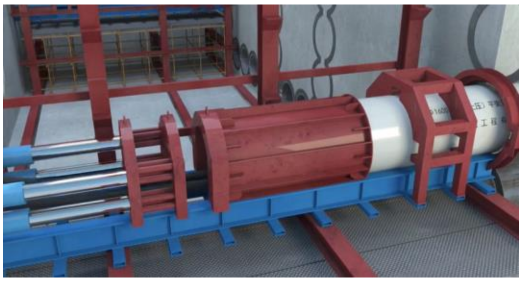


Figure 4: Five major advantages of systematic pipe curtain with RTBM methodology

4 Construction Sequences

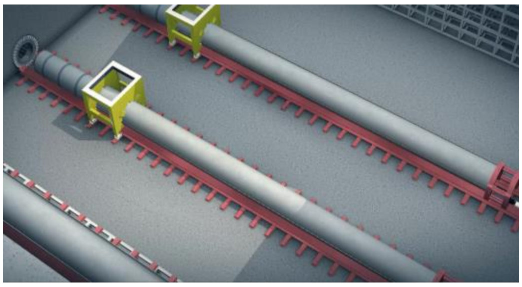
The construction sequences for pipe curtain RTBM methodology are mainly divided into two stages: One is pipe curtain installation and segment installation. The other is a common launching and receiving shaft that will be constructed for both activities, and its setup requirement is similar to a RTBM construction site.

***Step 1** - Setup*



Setup a jacking platform inside the launching shaft. The tunnel eye seal will be installed at each break-out location. Remove the sheetpile or RC wall at each break out position. Install and commission the pipe jacking machine and the supporting system. After the preparations are completed, pipe jacking will commence.

***Step 2** – Jack in the datum pipe*

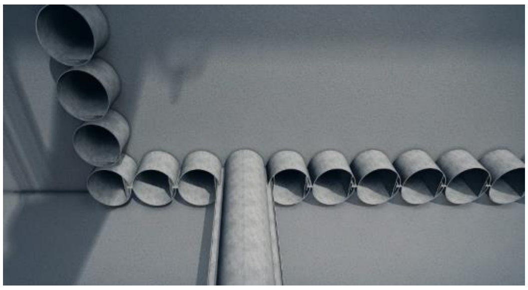


Pipe curtain steel pipe can be divided into three types: datum pipe, socket pipe and closure pipe. Both sides of the datum pipe are female locks, which is the starting point of the pipe curtain's construction, so it requires high precision control.

***Step 3** – Jack in socket pipe*

The lock of the socket-intubation pipe consists of a male lock and one or more female locks. After the jacking of the datum pipe is completed, insert the male lock of the first socket pipe into the female lock of the adjacent datum pipe, and then start the jacking of the subsequent socket pipes one by one. During the process, insert the male locks of the socket pipe into the female locks of the adjacent socket pipe in turn until the entire pipe curtain is about to close.

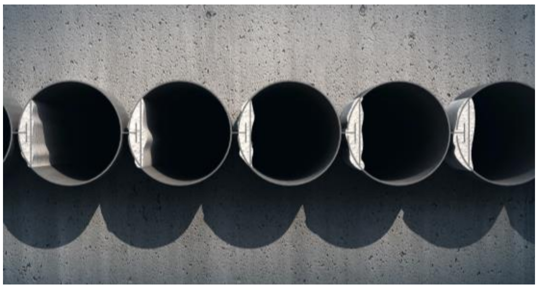
***Step 4** – Jack in closure pipe*



The lock of the closure pipe consists of one or more male locks. Each male lock of the closure pipe needs to be inserted into the female lock of the adjacent steel pipe to form a closed-up structure. In the process of pipe curtain construction, a pipe curtain system generally consists of one reference pipe and a closed pipe. In case of achieving a shorter construction period, multiple datum pipes and closure pipes can also be configured according to the programme to allow numerous pipes to be jacked simultaneously. In order to reduce the jacking resistance, lubricant grout will be injected into the female lock during the jacking process.

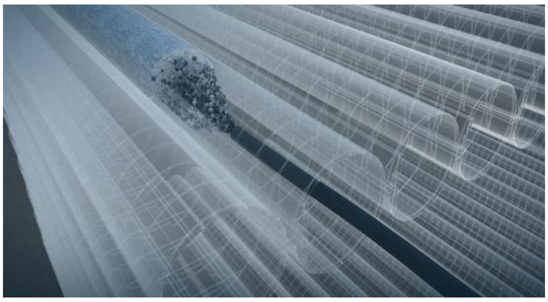
***Step 5** – Replacement grouting*

After the whole pipe curtain system is installed, replace the lubricant grout with high strength cementitious grout to reduce the post-construction settlement and improve the water tightness of the pipe curtain system.



***Step 6** – Concrete infill*

To ensure that the pipe curtain has good rigidity in the subsequent excavation process, self-compacting concrete is filled into the steel pipes. If stringent monitoring requirement is needed, monitoring devices can also be embedded into several steel pipes of the curtain together with the concrete infill to act as a monitoring datum before subsequent excavation work is conducted.



***Step 7** – Tunnel eye portal*

Finally, a tunnel eye portal will be constructed to join all the steel pipes together to form a pipe curtain ring beam. Thus, the closed steel pipe curtain is completed.

After the pipe curtain is completed, the soil within the curtain will be excavated. The excavation method can refer to the other technical paper regarding the jack-in-place segment RTBM methodology.

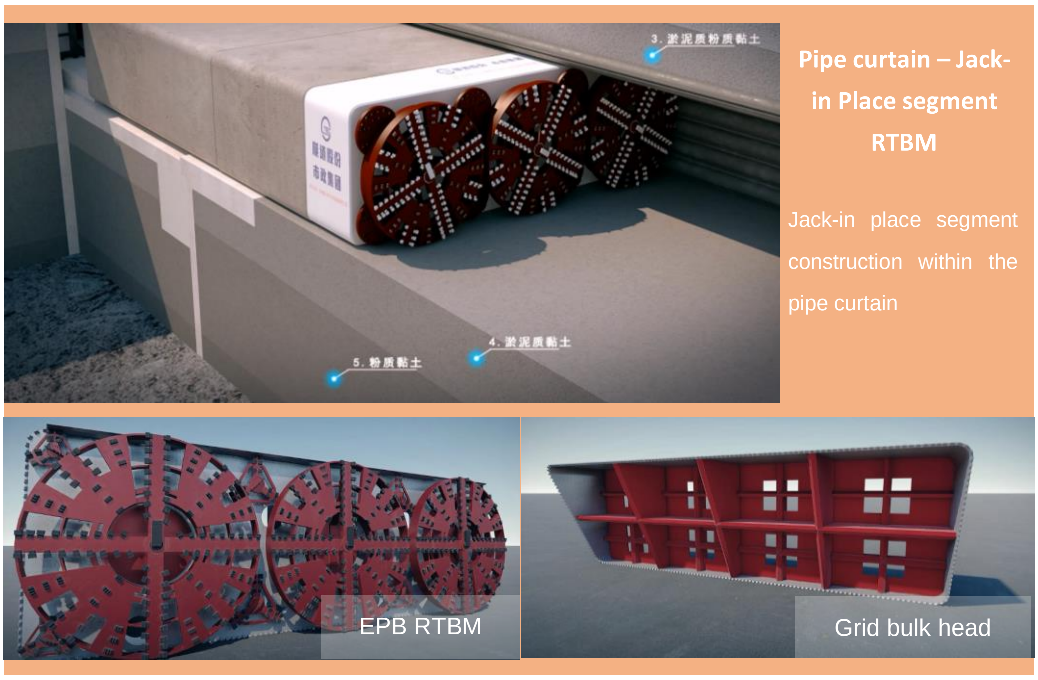


Figure 5: Jack-in place segment RTBM

According to the ground conditions, different types of drilling machines can be selected. The permanent structure can be cast in situ, prefabricated, or combined depending on the availability of construction space, logistics and lifting capacity. During the structure jacking process, the posture of the excavation machine can be precisely controlled by adjusting the synchronous jacking system and the front face pressure developed at the bulkhead of the excavation machine. The pipe curtain system, together with the RTBM technology, will provide double assurance to prevent excessive ground settlement even for wide span rectangular structures. Similar to the normal RTBM process, lubricant grouting will be injected during the process. Once all the permanent structures are jacked in place, the whole lubricant grouting will be replaced by annulus replacement grout to complete the entire process.

5 Case Study

5.1 Project Overview

Tian Lin Road underpass under the Middle Ring Road (Transportation Node Improvement Project on the Middle Ring Line)

Figure 6: Site setup on Tian Lin Road

The project is located in the middle of Cao He Jing Development Zone, Xuhui District (City center) in Shanghai, China. It is part of the transportation improvement project on Middle Ring Road and Tian Lin Road interchange which is a 1032.78 meters long expressway across the Shanghai city center. The starting and ending chainage of the underpass structure intersecting with the Middle Ring Road is at chainage K0+663~ K0+749, the underpass length is 86m, with the structure's top soil cover is 6.3m. The design cross-section of the underpass structure is 19.8m in width and 6.4m in height to allow three traffic lanes for two directions and two subway passages. In general, the whole structure is located in silty clay geology conditions.

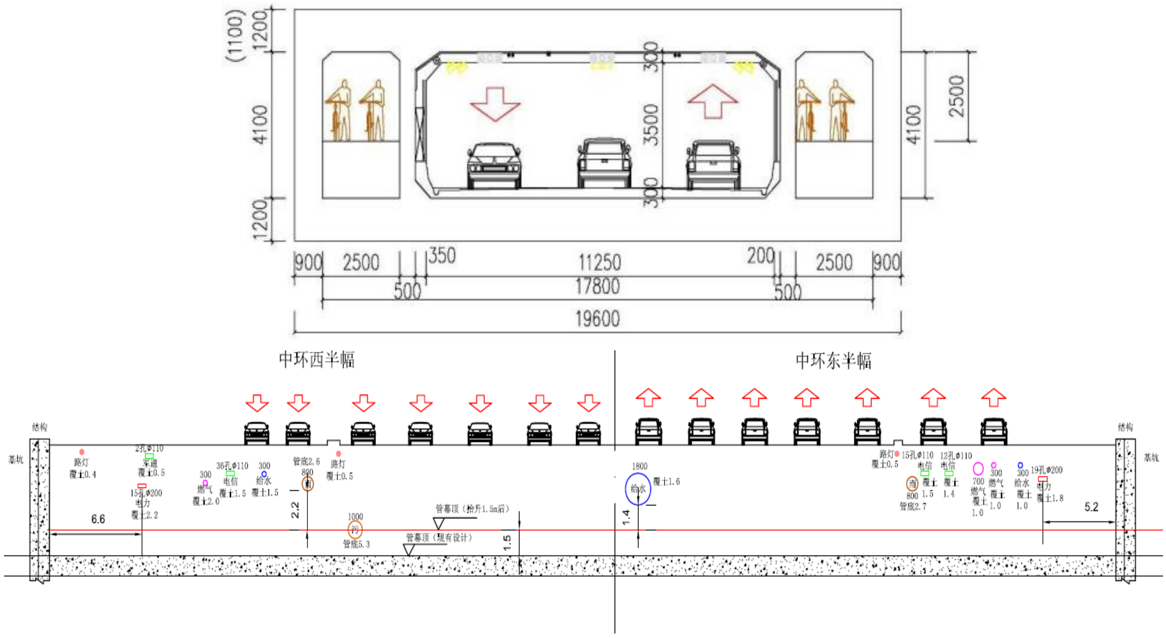


Figure 7: Tin Lin Road Underpass General arrangement

As shown in Figure 7, there are more than 20 nos of existing utilities/pipelines on the Middle Ring Road, which had intersected with the Tian Lin Road underpass structure, including electric power cables, communication cables, water supply pipelines, coal-gas supply pipelines, storm drain, sewage drain, and national defense optical cables. Among them the 1000mm dia. sewage pipe on the auxiliary road on the west side of the Middle Ring Road (the covering depth is about 4.2m) and the 1800mm dia. water supply pipe at the lower part of the central green verge of the Middle Ring Road (the covering soil depth is about 2.0m) are the closest to the top of steel pipe curtain. The minimum clear distance between the sewage pipe foundation and the top of the steel pipe curtain is only 0.5m.

5.2 Construction process design of the pipe curtain

A mini pipe jacking machine was used in advance to jack 62 steel pipes one by one at the outer periphery of the underpass. During the construction stage, four monitoring pipes were set up according to the jacking sequence of the steel pipe curtain. At the same time, in order to ensure the jacking accuracy of the pipe curtain and reduce the deformation of the underground pipeline and the settlement of the Middle Ring Road caused by multiple pipe jacking, the jacking sequence of the pipe curtain is as follows, first installing the lower row, then the upper row, from the middle pieces toward both sides. The side rows are installed from top to bottom.

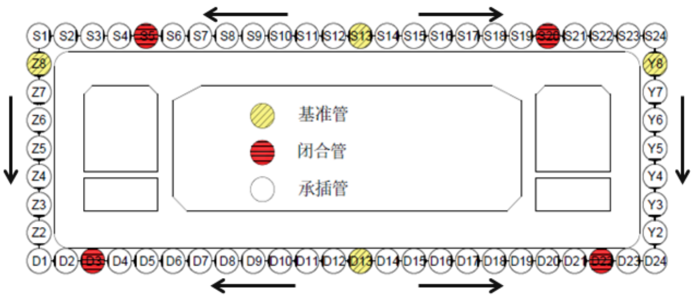


Figure 8: Pipe curtain jacking sequence

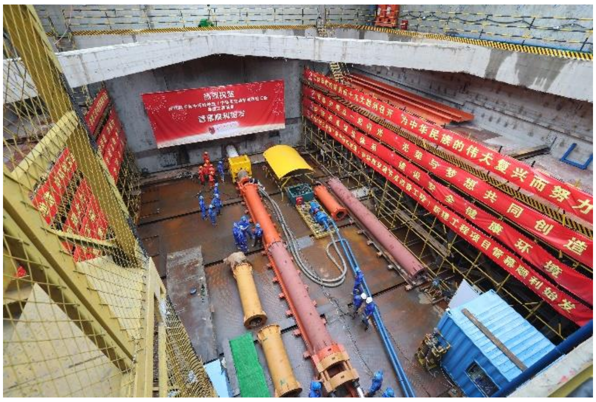


Figure 9A: Pipe curtain jacking in process

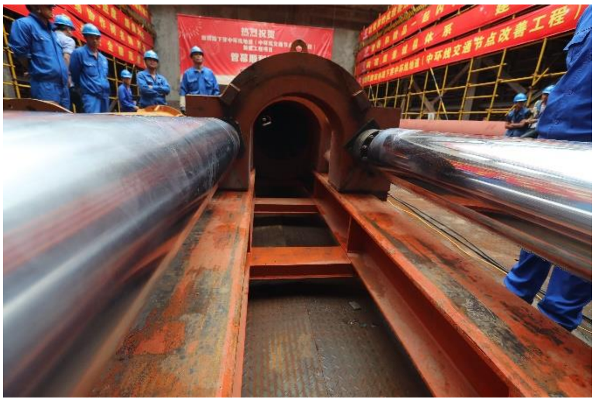


Figure 9B: Close up view of jacking cylinder

The construction tolerance between the steel pipe curtain and the underpass structure is set as follows: the upper row to the structure's top level is 10 cm, and the left and right sides are 10 cm.

The whole underpass structure is divided into five sections, the first section is 12.4m, and the last four sections are 18.8m each. Every section is constructed within the launching shaft and jacked forward one by one. A wide span EPB RTBM is deployed to muck out the soil within the steel pipe curtain. By controlling the active front face pressure of the machine, it can effectively control the deformation and settlement of the pipe curtain section during the excavation process. It is assumed that the surrounding frictional resistance to the circumference of the underpass structure is 20 kN/m2. During the construction stage, the actual measured maximum jacking force is 6,687 tons when the last section of the underpass structure (section 5) is jacked, which is equivalent to frictional resistance 5 kN/m2 on the circumference of the underpass structure. It has been proved that by using the automatic lubricant injection system, a lubricant layer is established between the pipe curtain and the underpass structure. The pipe curtain effectively reduces the loss of lubricant to the surrounding soil, thus reducing the requirement of total jacking force for the operation.

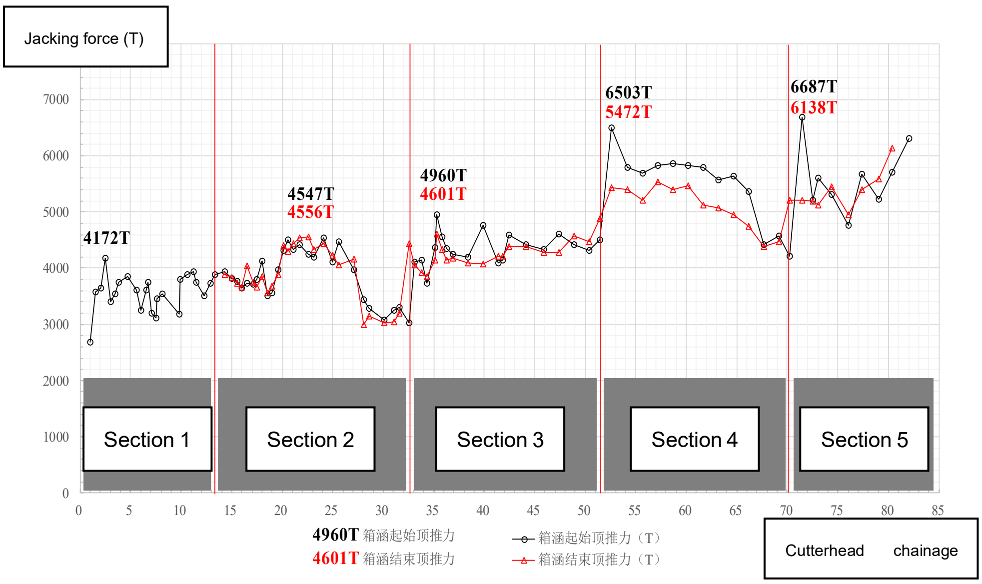


Figure 10: Measured jacking force during the segment jack-in process

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5.3 Equipment selection

The pipe jacking machine for the pipe curtain adopts the special pipe jacking machine for the 824mm dia. slurry machine.

Major components	Unit	Spec.
Machine dia.	mm	824
Length of machine	mm	3,600
Cutterhead power	kW	15
Torque	kN.m	23.3
Rotation speed	r/min	0—8
No. for articulation cylinder	Pcs	4
Articulation force	kN	375
Articulation cylinder stroke	mm	30
Re-adjusting angle	°	±2
Slurry pipe dia.	mm	100

Figure 11: Specification for the mini pipe jacking machine

The selection of the cutter head of the pipe jacking machine for the pipe curtain takes into account that the foundation of the underground pipeline is only 0.5m away from the pipe curtain. As the machine is relatively small in size using 100mm dia. slurry pipe, the gravel/cobbles fill near the pipeline foundation, which may block the slurry discharge pipeline during the construction, will be treated by the secondary crushing devices equipped with the machine to crush it down to less than 20mm. The opening ratio is adjusted to 8%, which effectively supports the front soil and reduces the settlement. The opening ratio is the percentage of opening portion on cutterhead to the total area of the cutterhead.

The RTBM's section is 19.84m×6.42m, and there is a 20mm overcut to the top and both sides of the underpass structure. There are three 6360mm dia. main cutterheads and eight small cutterheads setup at the blind spots, and the coverage reaches 92% of the whole section. The blind spots are provided with a splitting device and a high-pressure water injection port, further enhancing mucking out ability of the machine.

Figure 12: RTBM cutterhead and jacking arrangement

The main jacking system for the RTBM uses 70nos of 250T hydraulic cylinders, which are divided into seven groups. Each group of hydraulic cylinders is driven and controlled by an independent hydraulic pump station. The deviation value is monitored in real-time according to the laser target installed on both sides of the underpass. The output data of each group of pump stations are synchronously adjusted through the specialised PID control algorithm, and the hydraulic cylinder propulsion speed is controlled to achieve synchronous propulsion.

5.4 Data Analysis

5.4.1 Monitoring Plan on Middle Ring Road

A total of 12 cross-sections of ground vertical displacement monitoring points are set on Tian Lin Road and Middle Ring Road junction. Each section consists of 16 nos of monitoring points spanned across the main road and auxiliary road.

5.4.2 Observation During the Pipe Curtain Installation Stage

Ground settlement upto approx. 10mm was observed during the initial stage of pipe curtain installation. The subsequent review had concluded that this was induced by the high opening ratio on the cutterhead of the machine and high jacking speed during the initial drive. After the minor modification to the cutterhead and adjustment to the jacking operation, including the settlement control injection, the

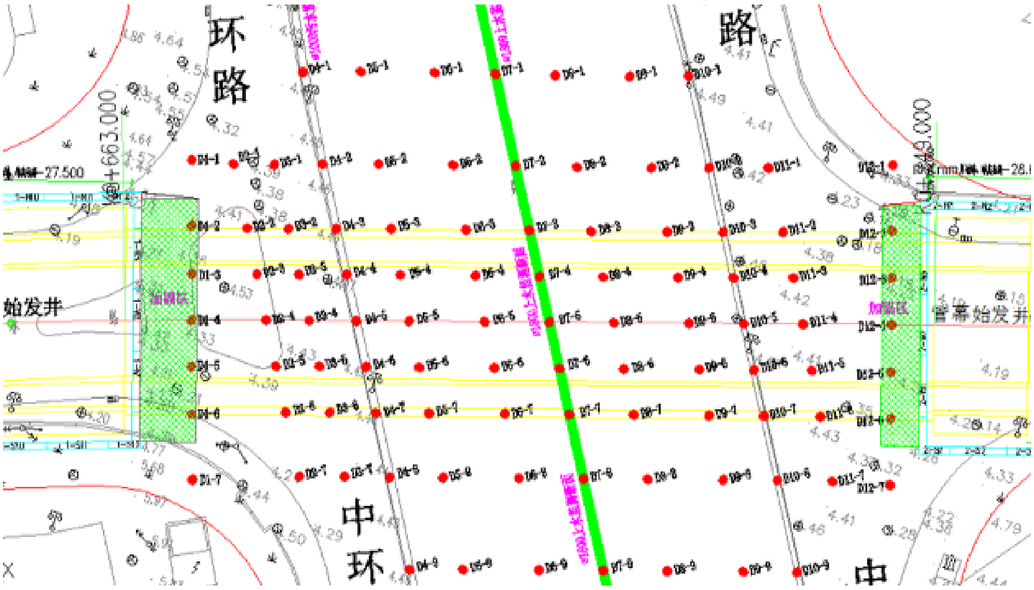

Figure 13: Monitoring plan on Tian Lin Road

ground settlement is effectively controlled after the initial drive. When all the pipe curtains work was completed, the total accumulated ground settlement was not exceeded 10mm. The monitoring points on the D4, D5, and D6 sections have indicated that about 15mm ground heave occurred, which is caused by the subsequent replacement grouting during the final stage of pipe curtain installation.

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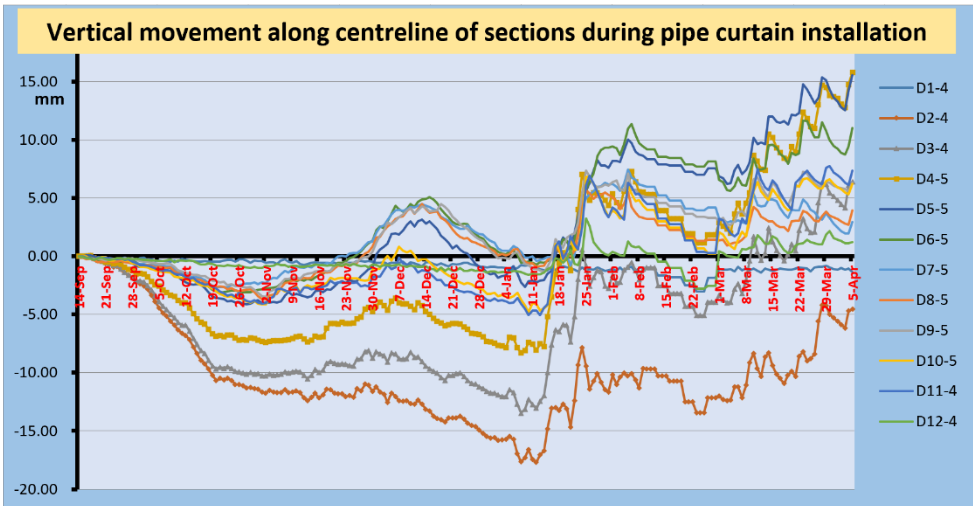

Figure 14: Ground settlement monitoring during pipe curtain installation stage

5.4.3 Ground Settlement and Observations During the RTBM Jacking Stage

The segment jacking is protected by the pipe curtain and the face pressure developed by RTBM; thus, the ground settlement can be effectively controlled. The maximum ground settlement during the process was limited to within 10mm. The face pressure monitoring mainly relied on the pressure sensors

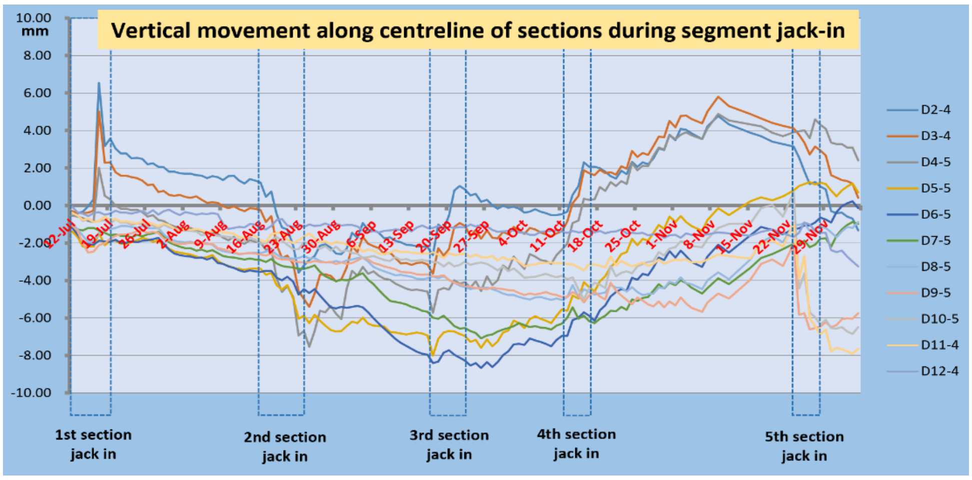

Figure 15: Ground settlement monitoring during RTBM jacking stage

installed along the vertical centerline portion of the machine. As multiple cutterheads were used for the machine, in reality, it can anticipate that uneven face pressure will be developed across the span of the machine. However, with the presence of pipe curtain, the adverse effect was minimized. The ground settlement of each cross-section of monitoring points along the main portion of the Middle Ring Road was further reviewed. It had revealed that the actual ground settlement is not affected by the potential uneven pressure during the segment jacking. The settlement curve across the underpass section still shows the settlement along the vertical centerline had the maximum value, which is in line with impact assessment prediction. It can be concluded with the protection of the pipe curtain, the ground settlement caused by the uneven active face pressure developed during the jacking operation, even for the wide-span section underpass, can be effectively alleviated.

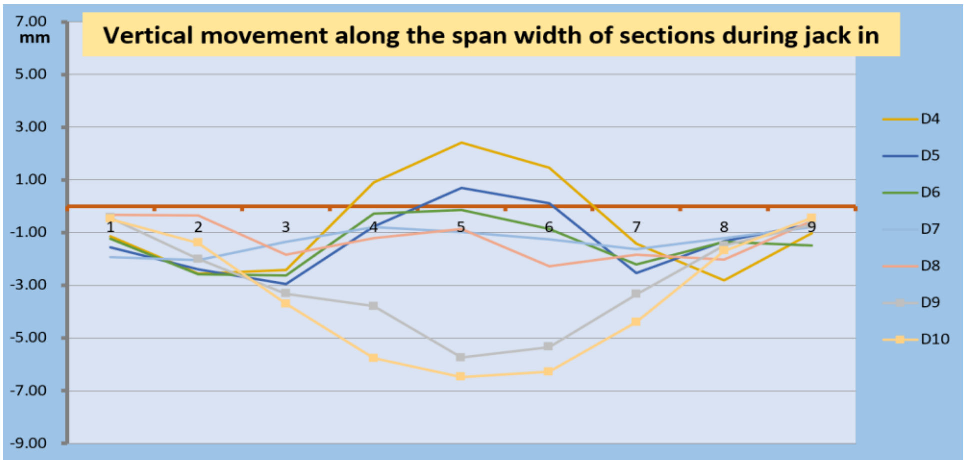

Figure 16: Settlement behaviour across the wide-span

6 Summary

1) The pipe curtain with jack-in place RTBM construction method can effectively solve the settlement effect caused by the "Segment Crown Soil Carrying Effect" induced during the rectangular TBM jacking operation and allow the trenchless construction of the underground structure with shallow soil cover and large section (>20m).

2) During the pipe curtain jacking stage, a minor settlement will occur to the ground surface due to the multiple disturbances resulting from pipe installation. The effect is minimal due to the fact that a small size jacking machine is in use. The effect can be further reduced by the replacement grout at the final stage of the work.

3) Special design pipe interlocking system can prevent the loss of the synchronous grouting slurry in the gap between the segment and the pipe curtain during the jacking stage, thus reducing peripheral friction resistance.

4) When constructing a large section box culvert, the protection of the pipe curtain can effectively reduce the risk of ground settlement caused by the uneven front face earth pressure developed by the machine induced by the disturbance of the multiple cutterheads arrangements.

5) In Hong Kong, we generally encounter fill, alluvium or colluvium with boulder mixed ground conditions. By the experience obtained from the local jack-in place segment RTBM projects, these typical Hong Kong geological profiles can be overcome by various cutterhead designs. With the enhancement of pipe curtain, we believe the RTBM technique can apply to underground space construction and provide a solution to overcome the current restraints that hinder the potential development, especially a structure with shallow soil cover and a wide cross-section area is required, for example, developing an underground shopping street that connects buildings in the town centre, and construction of vehicular underpass structures at a major road junction etc. This technique allows challenging projects to be built in a safe, high quality and high productivity manner.

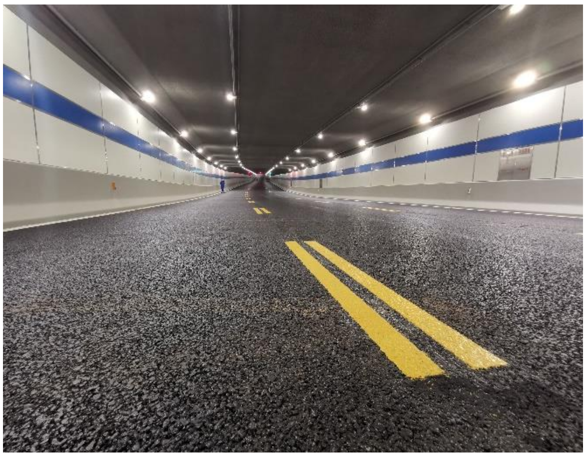

Figure 17A: The completed underpass

Figure 17B: Operation room of RTBM

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