

# Transforming Underground Linkway Construction: Rectangular Pipe Jacking Machine at Teck Ghee MRT

J.J.Foo, Q.L.Hong, Y.S.Chu, & D.Lee  
Shanghai Tunnelling Engineering Co. Pte. Ltd, Singapore

O.G.Machin, J.Y.Goh & J.Pang  
Land Transport Authority, Singapore

C.J.Chai  
LYL Consultants Pte. Ltd, Singapore

G.L.Tan  
Building and Construction Authority, Singapore

**ABSTRACT:** This study examines the application of the Rectangular Pipe Jacking Machine (RPJM) in Contract N109A for constructing two underground linkways at Teck Ghee MRT Station. Due to the constraints of a densely populated urban environment, with live roads, buildings, and numerous utilities, RPJM was chosen as the preferred construction method. This paper outlines the approach taken, detailing the construction methodologies, challenges encountered, and solutions implemented. Through strategic planning and sequencing, the project achieved significant program efficiencies, reduced manpower hours, and minimised disruptions to the surrounding area. A comprehensive back-analysis further provides key lessons learned and insights for future applications, reinforcing the benefits of RPJM technology in urban infrastructure projects.

## 1 INTRODUCTION

### 1.1 Project N109A

The Land Transport Authority's (LTA) project N109A is a complex and ambitious undertaking. It involves the construction of two critical infrastructure developments: the North-South Corridor (NSC) and the Cross Island Line's Teck Ghee MRT Station.

The NSC is a multi-modal transportation corridor designed to enhance connectivity between the northern region and the city. Meanwhile, Teck Ghee MRT Station is a key station on the Cross Island Line. The integration of these two major projects within N109A presents unique engineering challenges, requiring innovative construction methods and meticulous planning to ensure successful implementation.



Figure 1. N109A Layout Plan

### 1.2 Usage of RPJM in N109A

Teck Ghee MRT Station features six entrances, strategically designed to enhance commuter connectivity with the surrounding buildings. Among these, key entrances include Entrance 1 to 4, which are seamlessly linked by underground linkways passing beneath the live traffic road of Ang Mo Kio Avenue 1.

Initially, the construction of these linkways was planned using the cut-and-cover method. However, after further review, Shanghai Tunnel Engineering Co. (STEC) proposed the use of the RPJM to improve efficiency and reduce disruption. This proposal was subsequently accepted by LTA.

The RPJM method, utilising precast concrete segments, was ultimately adopted to minimise surface disruption, reduce construction time, and enhance safety, making it an efficient approach for tunnelling beneath a busy roadway.



Figure 2. Completed Linkway

Table 1. Profile of linkways.

	<b>Launch Shaft</b>	<b>Retrieving Shaft</b>	<b>Total Distance</b>
Linkway 1	Entrance 2	Entrance 1	36m
Linkway 2	Entrance 3	Entrance 4	56m

## 2 GEOLOGY

The RPJM alignment is mainly located within two geological formations: Kallang Formation and Bukit Timah Granite G(VI) and G(V), as identified in the Geotechnical Interpretative Baseline Report (GIBR) and bore-log data.

The figures below illustrate the soil profile for both linkways, with the launch shaft positioned on the left and the retrieval shaft on the right.

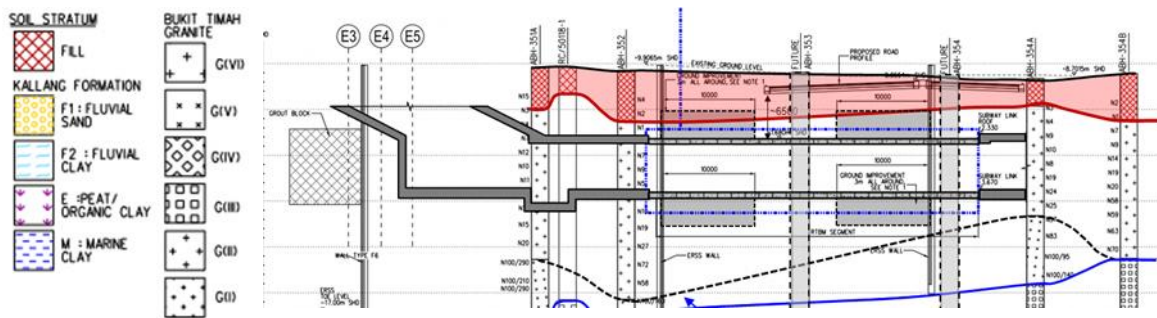


Figure 3. Linkway 1 Soil Profile

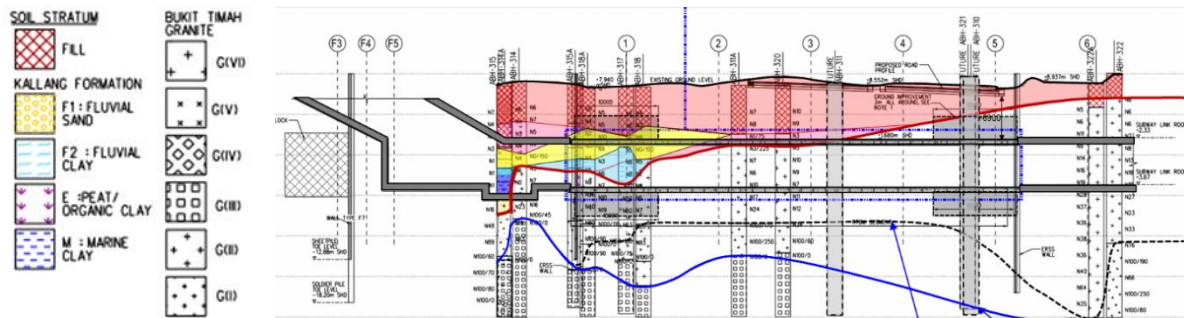


Figure 4. Linkway 2 Soil Profile

### 2.1 Shallow Overburden

The RPJM tunnel alignment primarily consists of fill material as overburden, with the shallowest overburden at approximately 7 meters deep. This relatively shallow overburden presents a significant risk during tunnelling operations, as the surrounding ground is susceptible to blowouts, heaves, or ground settlement, which could potentially affect road infrastructure and live utilities above the RPJM tunnel alignment. Therefore, the target face pressures that include both the upper and lower bounds need to be designed to ensure that the support medium within the excavation chamber does not escape and that stable support is maintained to prevent any tunnel face collapse. (Bernard et al. 2019). Additionally, extensive instrumentation monitoring and control measures were implemented in Contract N109A to mitigate these risks.

### 2.2 Bukit Timah Granite (G(VI) and G(V))

The RPJM drive was completed predominantly through Bukit Timah Granite Formation, with weathering grades such as G(VI) – residual soil, and G(V) – Completely Weathered rock (Sigl, 2024). This residual soil is typically clayey and silty is considerably weak and can be crumbled by hand. However, these ground conditions are considered advantageous for tunnelling, as the RPJM used in Contract N109A is an Earth Pressure Balance (EPB) mode, which turns excavated material into a soil-paste support medium through the injection of bentonite and foams for soil conditioning. This creates a stable tunnel face suitable for mining through the shallow overburden tunnel alignment.

### 2.3 Kallang Formation

The presence of Kallang Formation, which consists of Fluvial Sand (F1) and Fluvial Clay (F2) layers, was identified near the launch shaft of Linkway 2, posing additional challenges during the RPJM mining operation. Kallang Formation was located at a depth of approximately 6.5 to 10 meters below ground level and extends 20 meters along the tunnel alignment. F1 layers are known to present challenges due to their loose, non-cohesive and high permeability in nature. Likewise, the F2 layer is typically sandy clay/silt and cohesionless. Such ground conditions can lead to an uncontrollable flow of unstable sand/clay material and water into the RPJM excavation chamber, increasing the risks of over-excavation, which may result in ground settlement and potential surface sinkholes on the live road above the tunnel alignment.

To mitigate such risks, it is critical to maintain adequate face pressure and conditioning of the soil to support the soft and cohesionless ground during tunnelling operations until the tunnel segments are installed (Broere 2001).

Apart from maintaining the required face pressure, the RPJM EPB shield also mitigates the associated risks when tunnelling through the Kallang Formation. The EPB system allows precise control of the screw conveyor speed, which controls the amount of excavated material being transported from the base of the excavation chamber onto the muck skip. This is particularly crucial when tunnelling under loose or cohesionless ground conditions in the Kallang Formation. The RPJM used in Contract N109A is equipped with a double screw conveyor system to effectively regulate the flow of soil and control the face pressure on the tunnel face, mitigating any risks of instability or tunnel face collapse. Furthermore, ground improvement by Jet Grout Pile (JGP) and Tube a Manchette (TAM) grouting was carried out as precautionary measures to strengthen the Kallang Formation layer and reduce its permeability, which further mitigates the associated risks.



Figure 5. RPJM Double Screw Conveyor System for controlled muck disposal

### 3 RPJM DESIGN

The RPJM used in the N109A project is based on a machine originally deployed in a completed project by STEC, where an underground linkway was successfully constructed beneath live roads. The linkway dimensions in both projects are comparable, with similar tunnel sizes, making the reuse of the RPJM a practical and efficient choice. This not only optimises resources but also demonstrates the adaptability of the machine in similar tunnelling conditions.

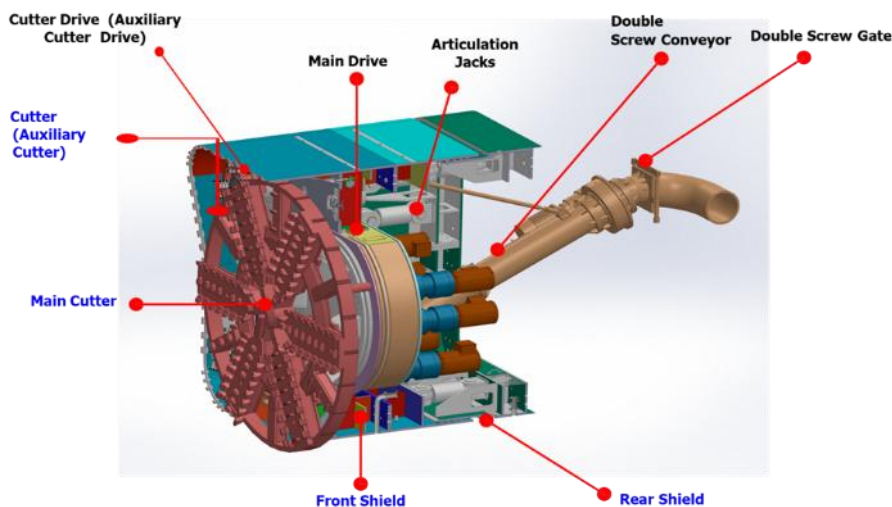


Figure 6. RPJM Main Components

### 3.1 Refurbishment from the Funan Project

To adapt the RPJM for use in N109A, a refurbishment process was carried out to improve its operational efficiency. While the core design of the machine remained the same, the upgrades were made to ensure better performance and safety during the tunnelling process.

Table 2. Funan and N109A RPJM Specification comparison.

		Funan	N109A
RPJM Type		EPB	
Machine Length		6160 mm	
Machine Width		7630 mm	
Cutterhead Exposure		Fully Enclosed	Main Cutter exposed
Cutting Profile		87 %	91.8 %
Main Cutter	Diameter	6400 mm	6430mm
	Speed	0-1 r/min	0-1 r/min
	Power	792 kW	792 kW
	Torque	5055 kN	5055 kN
Auxiliary Cutter 1	Diameter	1920 mm	2170mm
	Speed	0 – 2.5 r/min	0-2.5 r/min
	Power	37 kW	45kW
	Torque	140 kN	165 kN
Auxiliary Cutter 2	Diameter	1 m	1 m
	Speed	0 – 7.5 r/min	0-7.5 r/min
	Power	11 kW	22 kW
	Torque	14 kN	28kN

### 3.2 Cutterhead Exposure

In the original Funan tunnel project, all cutterheads were enclosed within the front shield, and the tunnel cross-section was supported by this casing during jacking. While this design provided structural stability, it also significantly increased jacking resistance, making tunnelling less efficient. Additionally, the cantilevered cap structure of the front casing posed a risk of deformation when encountering weak soil conditions.

For the N109A project, the design has been modified to enhance cutting efficiency and reduce jacking resistance. The front shield has been recessed to increase the cutterheads' exposure, allowing the Main and Auxiliary cutters to cut through the soil more effectively. This change improves penetration rates and reduces overall thrust force requirements.

Isometric View

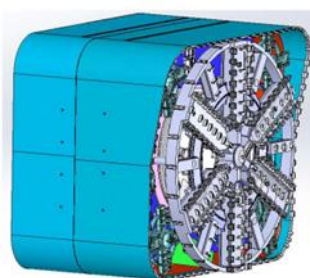


Figure 7. Funan RPJM Cutter

Top View + Isometric View

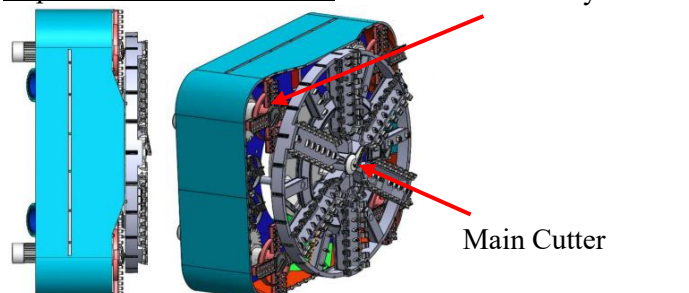


Figure 8. N109A RPJM Cutter

### 3.3 Cutterhead Exposure

During the Funan project, instances of "jamming" occurred in the lower small auxiliary cutterhead. Analysis suggests that this issue may have been caused by the cutterhead's low cutting efficiency

(insufficient torque), along with the ineffective performance of soil improvement additives. These factors led to poor soil flowability in the area, resulting in soil accumulation.

To address this, the design includes increasing the main cutterhead and auxiliary cutter 1 diameters to expand the overall cutting coverage. The figure below shows that the Cutting Profile ratio of N109A's RPJM is slightly larger (4.8%). Additionally, the drive power and torque of the intermediate and small cutterheads were enhanced.

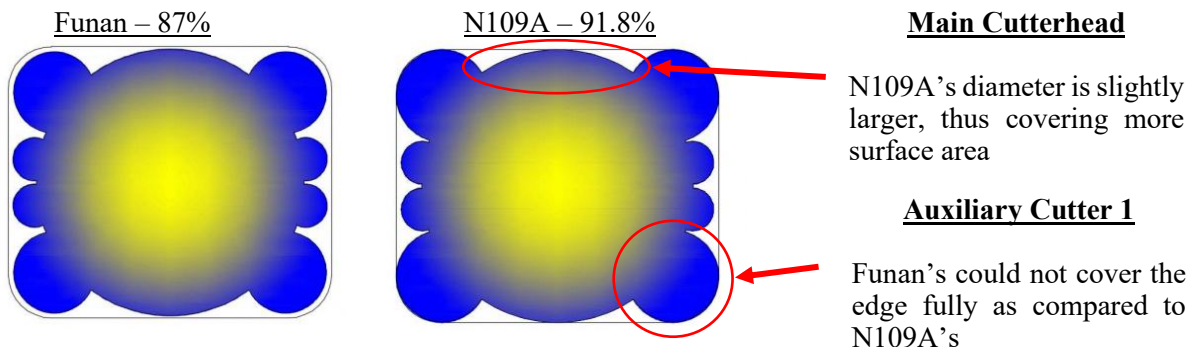


Figure 9. Cutting Profile Comparison

## 4 RPJM OPERATION SET-UP

### 4.1 Thrust Jack

The thrust jacks are the primary driving force behind the RPJM, responsible for pushing the machine and pipe segments forward through the ground. The required force depends on geological conditions and friction along the jacking path, with a maximum thrust force of 46,000 kN used in N109A.

Thrust speed is another critical aspect that requires careful control. If the machine advances too quickly, it can destabilise the surrounding soil, leading to potential collapses or misalignment. Conversely, if the jack speed is too slow, excessive friction can build up, increasing resistance and making progress more difficult. The jacking speed at N109A is controlled at a maximum of 40 mm/min, ensuring smooth and stable tunnelling progress.

### 4.2 Anti-Reverse Frame

To prevent segment rebound after jacking, an anti-reverse frame is installed as a critical support structure. Once a segment is pushed forward, it needs to remain in place to avoid shifting backwards due to soil pressure or elastic rebound.

If segments move back even slightly, the required jacking force may become insufficient, leading to delays or machine stalls. By implementing an anti-reverse frame, the segments are securely locked in position, ensuring continuous forward movement without setbacks.

### 4.3 Back-Up Gantry (BUG)

The BUG remains on the surface throughout the operation, as the short tunnelling distance eliminates the need to bring it underground. Unlike longer tunnel drives, where BUG may need to be relocated behind the RPJM as the machine advances, this setup allows continuous surface-based supply without requiring conversion. Essential materials such as water, bentonite, and hydraulic fluids are efficiently delivered through the umbilical hose, ensuring uninterrupted operation. This approach not only saves time but also simplifies logistics, reducing downtime and enhancing overall efficiency in the RPJM process.

#### 4.4 Control Room

The control room is situated out of the RPJM, serving as the command centre for RPJM operations, where operators can monitor and adjust the machine's performance in real time. It is equipped with digital interfaces that display key data such as jacking force, thrust speed, face pressure, and alignments.

Connected to the RPJM via cables, the control room allows operators to remotely manage various aspects of the tunnelling process, such as adjusting thrust force or modifying soil conditioning parameters.

#### 4.5 Electricity Supply

The RPJM operation is powered by a 400V supply, supported by three 700 KVA generators operating in synchronisation with automatic switching to ensure a stable and uninterrupted power source.

Electricity is distributed through 20 low-voltage (LV) cables running within the tunnel, supplying power to all critical systems. At the shaft bottom, a specially designed Distribution Board (DB) box with quick sockets enables fast and secure connections, minimising downtime and improving operational efficiency.

During segment installation, cables must be frequently removed and reconnected. If high-voltage cables were used, a Professional Engineer (PE) would need to supervise each connection and disconnection, leading to significant delays. By switching to LV cables, the team can handle these connections independently, allowing for smoother operations and reducing downtime.

## 5 CONCRETE SEGMENT

### 5.1 Segment Design

#### Dimension

The dimension of the Segment is as shown in the table below:

Table 3. Segment Dimension

<b>Segment Outer Dimension</b>	7600 x 6400 mm
<b>Segment Inner Dimension</b>	6600 x 5300 mm
<b>Thickness</b>	550 mm (Top and Bottom), 500 mm (Sides)
<b>Width</b>	1500 mm
<b>Weight</b>	53 ton

#### Ports and Sockets

Table 4. Types of Ports and Sockets in the Segment

<b>Lubrication Port (a)</b>	10 nos	<ul style="list-style-type: none"> <li>Bentonite Injection during mining</li> <li>Replacement grouting after tunnel completion</li> </ul>
<b>Grout Port (b)</b>	3 nos	<ul style="list-style-type: none"> <li>Grout injection in case of settlement</li> <li>Assist in lifting works inside the tunnel</li> </ul>
<b>Demoulding Socket (c)</b>	4 nos	<ul style="list-style-type: none"> <li>Segment demoulding</li> <li>Segment handling</li> </ul>
<b>Turning Socket (d)</b>	2 nos	<ul style="list-style-type: none"> <li>Turning the segment into a vertical position</li> <li>Socket for anti-reverse pin</li> </ul>
<b>Lifting Pin (e)</b>	4 nos	<ul style="list-style-type: none"> <li>Segment installation</li> </ul>

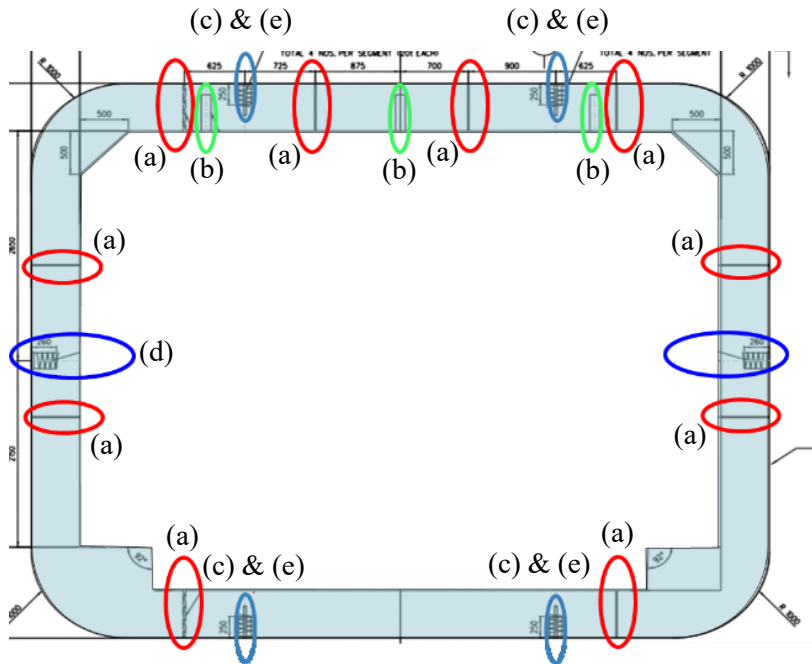


Figure 10. Segment Port and Sockets Locations

### Segment Accessories

Segment accessories play a critical role in ensuring the stability, water-tightness, and overall integrity of tunnel linings in the tunnelling process.

**Steel Collar:** The steel collar is an essential component used to reinforce the tunnel lining segments. It provides added structural strength and helps ensure the proper alignment of segments during installation. The collar is typically attached to the edges of the segments and contributes to the overall durability of the tunnel, especially in areas where additional reinforcement is needed.



Figure 11. Segment with Steel Collar (Bottom)

**Double Wedge Gasket:** This is used for sealing between the tunnel lining segments to prevent water ingress and ensure the tunnel remains dry. The gasket is placed in the joint between two adjacent segments and is designed to deform under pressure, forming a tight seal. This dual-layer gasket is highly effective in maintaining water-tightness, even under challenging conditions, and helps reduce the risk of leaks that could compromise the tunnel's integrity. A test was done to check the gasket's performance under pressure and water resistance conditions.

**Hydrophilic:** Hydrophilic seals are used to enhance the water resistance of tunnel linings. These seals expand when in contact with water, creating a tight seal that prevents water from entering the tunnel. The hydrophilic material is typically applied to the joint areas of the tunnel segments. As the tunnel

lining comes into contact with moisture, the seal swells, ensuring a strong, long-lasting barrier against water infiltration, which is critical for maintaining the tunnel's structural stability over time.

### 5.2 Segment Casting

The concrete segments used for the RPJM tunnel are cast in an external casting yard located in Pioneer. A key aspect of the casting process is the use of a single set of steel moulds. Since only one set is available, it is continuously reused for each new segment, making careful maintenance and handling of the mould crucial to prevent defects and ensure consistency in the segments produced.

The casting program primarily follows the demand of the N109A site. However, a critical factor in planning is the availability of storage space at both the casting yard and the construction site. Proper coordination is essential to avoid congestion, ensuring that segments are delivered promptly without overloading either location. This balance helps maintain efficient production and smooth logistics throughout the project.

### 5.3 Logistic

To ensure seamless and efficient delivery, each transport operation utilises 10-axle Cometto trailers, each carrying two concrete segments from the Pioneer casting yard to the N109A site. Due to the oversized nature of the concrete segments, these deliveries are scheduled at midnight to minimise traffic disruptions and comply with transportation regulations. Escorts are arranged to guide the transport, ensuring safety and proper handling of the oversized items.



Figure 12. Segment Delivery

## 6 CONSTRUCTION APPROACH

Construction of Linkway 2 was carried out first. Upon breakthrough at the receiving shaft, the RPJM, along with essential equipment such as thrust jacks, BUG, generators, and other necessary tools, was dismantled and transported to Entrance 2 for reuse in the construction of Linkway 1.

Linkway 2 has since been successfully completed, and works on Linkway 1 are currently in progress and nearing completion.



Figure 13. RPJM Breakthrough at Entrance 4

### 6.1 Site Utilisation Plan

The figure below showcases the site utilisation plan for Linkway 2, highlighting the shafts and the equipment surrounding them. The layout optimises the use of space and resources, ensuring efficient workflow while accommodating all necessary equipment and operations.



Figure 14. Site Utilisation Plan for Linkway 2 (Ent 3 on the left, Ent 4 on the right)

The shafts for the RPJM are not specially created just for the tunnelling operation. After the completion of the tunnelling works, these shafts will also function as the entrances for the linkways. This approach eliminates the need for duplicate construction efforts, as the same shafts are efficiently utilised for both the RPJM setup and as access points for the linkway. By integrating these functions, we avoid unnecessary duplication of work and resources, streamlining the construction process and optimising the use of space.

### 6.2 Lifting Works

Typically, gantry cranes are used for such heavy lifting operations, particularly in tunnel construction projects, due to their stability and ability to handle large, heavy loads. However, in this case, mobile cranes were chosen instead. Using mobile cranes provides more flexibility, as they can be easily repositioned as needed to accommodate different stages of the assembly and disassembly process. This approach was adopted due to site constraints and the need for quick mobilisation of equipment.

To facilitate the assembly and disassembly, two cranes were mobilised at each shaft: one being the main crane and the other, the tandem lifting crane. Since some of the heavy components of the RPJM cannot be lifted with just one crane, the tandem lifting approach is adopted. This method ensures precise control

and safety when handling these large, heavy components of the RPJM, enabling efficient and secure lifting operations.



Figure 15. Tandem Lifting

### 6.3 Ground Improvement Works

#### JGP Grouting

JGP is used to form the grout blocks at the breakthrough points of both the launch and receiving shafts. In the launch shaft, the face pressure takes some time to build up, and during this period, the grout block plays a critical role in stabilising the soil. The grout block ensures that the surrounding soil does not collapse or become unstable while the face pressure gradually increases.

At the receiving shaft, the face pressure must be kept very low to prevent soil movement or collapse. Here, the grout block again acts as a stabilising force, ensuring that the soil remains intact and secure during the entire process.

The dimensions of the grout block are designed to cover the entire RPJM, with an additional 2 meters of coverage beyond the machine's dimensions. This extra coverage ensures that the grout block fully stabilises the soil around the RPJM, providing a secure foundation and preventing any unexpected shifts or collapses in the tunnel face.

To ensure the effectiveness of the grouting, core tests were conducted to verify their strength and permeability. These tests help confirm that the grout has been properly set and provide the necessary soil stabilisation at both the launching and receiving shafts.

Additionally, probe drilling tests were carried out from the tunnel eye to check for potential water ingress at both the launch shaft and the receiving shaft.

### 6.4 Tunnelling Operation

The mining phase is a highly coordinated, round-the-clock operation involving two teams working in shifts. Each team is made up of Tunnel Managers, Tunnel Engineers, Supervisors, Mechanics, RPJM Technicians, and workers. The day shift focuses on segment installation, while the night shift handles the mining and prepares the site for the next segment.

On average, 1.5 meters are mined daily, and one segment is installed per day shift, ensuring continuous progress and that tunnelling operations stay on schedule.

### 6.5 Key Performance Indicator (KPI)

#### Face Pressure

In the tunnelling operation, the RPJM operator plays a crucial role in ensuring that the machine operates within the design parameters to maintain proper tunnelling conditions. One of the key parameters that the operator must closely monitor and adjust is face pressure, which is critical for the integrity of the tunnel and the safety of the operation. The face pressure must be maintained within a specific range,

typically between 1.2 to 1.7 bar, to ensure that the surrounding soil remains stable and that the machine operates efficiently.

Muck Skip Reconciliation

Muck Skip Reconciliation is a critical factor in maintaining proper excavation conditions to avoid under- or over-excavation. The process begins with the soil being loaded into the muck skip, which is then transported by a remotely controlled muck truck to the shaft opening.

Once at the shaft opening, the crane hoists the muck skip, and during this hoisting process, the weight of the soil is measured. This weight provides an accurate measure of the volume of material being excavated. By cross-referencing this weight with the expected excavation volumes, operators can ensure that the excavation is proceeding as planned. If any discrepancies are detected, adjustments can be made to maintain the correct excavation level.

After the hoisting, the soil is disposed of in the muck pit, completing the cycle. This system ensures precise excavation, helping to maintain the integrity of the tunnelling operation.

The graph below shows the volume loss throughout the construction of Linkway 2. The allowable limit for volume loss is set at +/- 15%, and as shown in the graph, the actual volume loss remains within this limit, showing that the excavation process is carried out efficiently and safely without causing significant settlement or environmental impact.

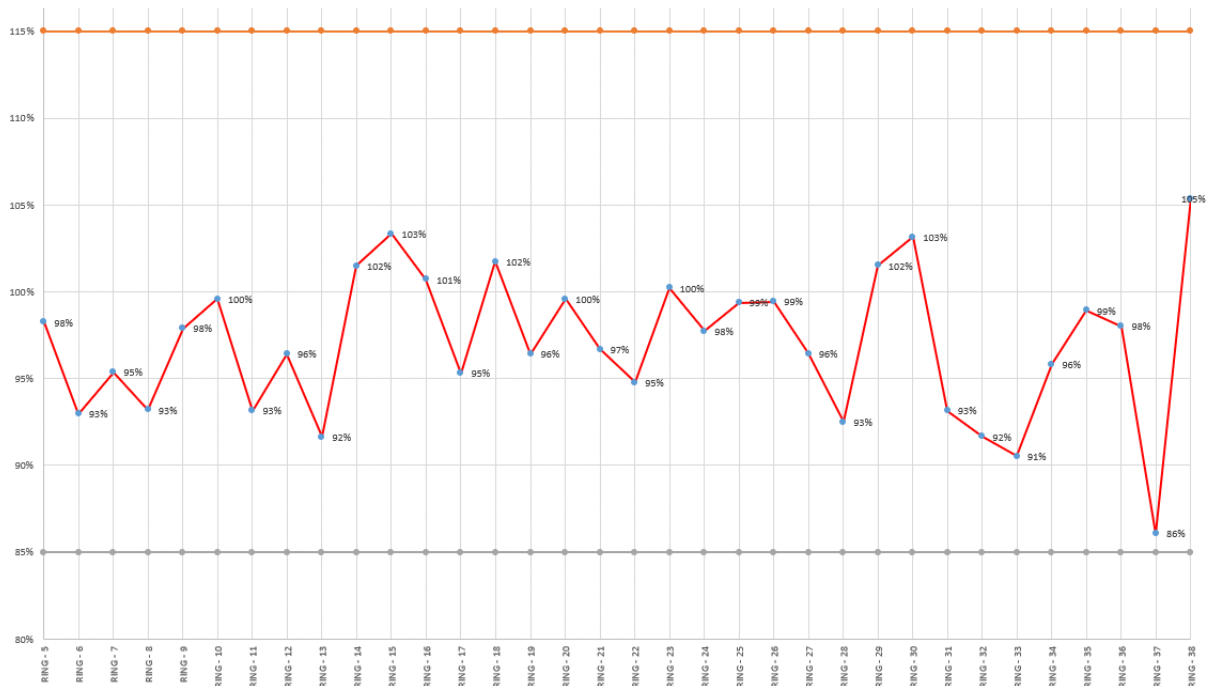


Figure 16. Volume Loss Graph

6.6 Soil Conditioning

Soil conditioning is a vital part of the tunnelling process. Bentonite and foams are injected through the cutterhead into the soil ahead of the tunnel face. This helps to stabilise the ground, soften the soil, and reduce friction, allowing for smoother excavation. The conditioning process also helps to manage groundwater and maintain the integrity of the tunnel face, ensuring continuous and efficient tunnelling operations.

Before the start of tunnelling, trial tests were conducted on the actual soil to determine the optimal soil conditioning parameters. These tests helped ensure that the right mix of bentonite and foam was used to effectively address the specific soil conditions encountered during the excavation, contributing to the overall success of the project.

### 6.7 Alignment Control

To keep everything on track, alignment is constantly monitored using a surveying system supplied by ENZAN, which provides real-time adjustments. This system ensures precision, so we hit our target breakthrough mark without fail.

The maximum deviation observed was 45mm, with 50mm as the allowable limit. To address this, measures were implemented to bring the RPJM back within the specified limits. One such measure involved using the articulation cylinder in the RPJM, which helps correct the alignment and ensure that the machine stays on track.

Additionally, bentonite pumping was used as a means to help push the RPJM back into alignment. For example, if the machine deviated to the left, bentonite was pumped to the left side of the installed segments, helping to push the RPJM back to the centre. This technique, combined with the articulation cylinder, ensures the RPJM maintains its optimal alignment and helps achieve a precise breakthrough, fitting perfectly into the tunnel eye.

### 6.8 Cutterhead cutting direction

The left and right-side auxiliary cutters of the RPJM are driven in opposite directions, which helps distribute the soil evenly across the cutterhead. This dual-directional movement prevents all the soil from being concentrated on one side, ensuring a balanced excavation process. As a result, the soil can exit more efficiently through the two screw conveyors, allowing for smooth and consistent muck removal throughout the tunnelling operation. This balanced soil distribution plays a critical role in maintaining the stability of the tunnel face and ensures that the muck-handling system operates without blockages or disruptions.

### 6.9 Segment Handling and Installation

#### Spread Beam

The spiral beam is used to unload the segment, which typically arrives in a resting (horizontal) position. To unload it, a Spiral Beam is hooked onto the crane and then placed on top of the segment. Four pins are manually locked into the demoulding sockets of the segment, and once secured, the segment is shifted to the desired location for further handling using the crane.



Figure 17. Shifting of Segment using Spread Beam

#### Remote Segment Tilting Device

A remote-controlled spread beam is used to turn the segment from a horizontal resting position to a standing vertical position. The spread beam is attached to the crane, and the pins of the spread beam are locked into the turning sockets of the segment remotely. Once locked, the crane will hoist the segment to a certain height, the spread beam then remotely rotates the segment to the vertical position, and places it on flat ground.



Figure 18. Turning of Segment from Horizontal to Vertical

### Installation of Segment

Before turning the segment vertically, the lifting lugs and wire rope are carefully attached to the designated lifting points on the segment. It is also crucial to ensure that the thrust cylinders on the shaft bottom are fully retracted to provide sufficient space for segment installation. Additionally, the previously installed segment must be securely locked into the anti-reverse frame.



Figure 19. Lifting Lug and Wire Rope attached to the segment

Once all preparations are complete, the segment can be turned vertically. After the spread beam is removed, the crane attaches the wire rope, lowering the segment to the shaft bottom for installation.

## 7 INSTRUMENTATION AND MONITORING

Before tunnelling operations began, a comprehensive impact assessment was conducted to evaluate the potential risks to the surrounding environment, including settlements, live roads, and utilities. This assessment ensured that appropriate measures were in place to mitigate these risks during the tunnelling process.

During tunnelling, several risks need to be carefully managed, including the risk of settlement, the potential impact on live roads, and the possibility of damaging utilities. These risks are particularly significant when the nearest utilities (sewer) are 1.67 meters away from the top of the RPJM for linkway 2 construction.



keeping the settlement within this limit, we can ensure that tunnelling operations proceed without causing any significant disruption to nearby structures, utilities, or live roads.

The graph below shows the instrumentation readings from the start of mining to the breakthrough.

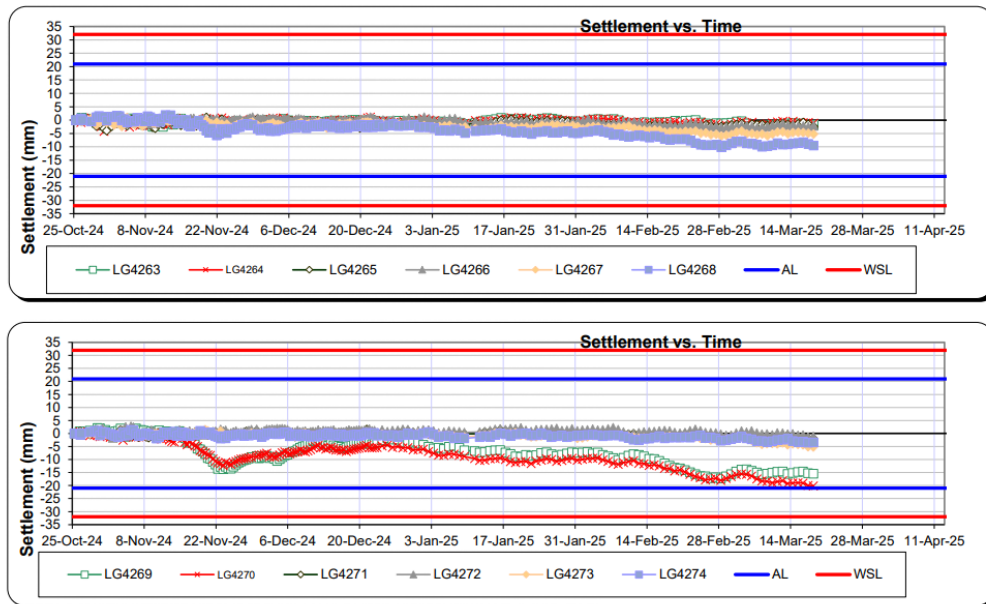


Figure 22. Settlement vs Time Readings

### 7.3 Settlement Control

Sometimes, settlement may approach the alert level of 20mm during tunnelling operations, requiring prompt action to ensure the safety and stability of the surrounding areas. To prevent it from settling further, measures must be taken to restore the ground to a safe condition.

In our case, Jello mud is pumped through the segment grout ports to slightly heave up the settlements and bring them back within the safe values. This method allows for controlled lifting of the affected areas, preventing further settlement while ensuring minimal disruption to surrounding infrastructure. The Jello mud consists of the following components: Polymer, Bentonite, and Water.

The pressure applied is 2.0 bar, and the average amount pumped per ring is 1.2m<sup>3</sup>. The Jello mud is only pumped when necessary to correct settlements, as excessive heaving can lead to other issues. This careful approach helps maintain stability and ensures the tunnelling process remains safe and efficient.

## 8 LESSONS LEARNT AND FUTURE RECOMMENDATIONS

### 8.1 Auxiliary Cutter 2 enhancement

During the final few meters of the tunnel drive, one of the Auxiliary Cutter 2 stopped turning. It was suspected that something had clogged the cutter.

Despite the malfunctioning cutter, tunnelling continued as usual. Since the stopped cutter was located at the rear and was relatively small, it had minimal impact on the overall excavation process. The main cutterhead continued to function effectively, covering the required excavation area and ensuring that tunnelling progress remained smooth.

Upon breakthrough, inspections revealed that a solid grout block had become lodged in the malfunctioning small cutter. Fortunately, as the main cutterhead had already cleared the tunnelling path, this issue did not disrupt the progress. The grout block was removed without any significant impact on the structural integrity of the tunnel or delays to the project timeline.

To improve future performance and prevent similar occurrences, increasing the power and torque of the small cutter is recommended. This would enhance its ability to handle blockages and ensure smoother operation.

## 8.2 Muck Skip Disposal

One of the limitations faced during the tunnelling operation is the restricted capacity of the muck skip. The safe lifting load for the muck skip is 12 tonnes. However, the skip itself weighs approximately 1.7 tonnes, and due to soil often sticking to the inner surfaces and not being fully discharged, the effective weight of an "empty" muck skip can reach up to 5 tonnes. This leaves only about 5 to 6 tonnes of available capacity for excavated material per cycle to maintain a safe working margin.

Given the average excavation rate, these 5 to 6 tonnes of muck correspond to roughly 5 minutes of excavation—approximately 60 to 80 mm of TBM advance. The skip fills up quickly and must then be lifted and disposed of, a process that typically takes 20 to 30 minutes. This creates a bottleneck, as excavation must pause until the empty muck skip returns, significantly affecting tunnelling productivity.

One of the most effective and straightforward solutions is to increase the size of the muck skip, thereby extending the time between disposal cycles and enabling longer continuous excavation. However, this is subject to constraints such as the size of the launch shaft opening, which may limit how large the muck skip can be.

Another potential improvement is to change the material or apply a non-stick lining to the skip's interior surface, reducing soil adhesion and allowing for cleaner discharges. This would lower the residual weight and improve skip turnaround time. Alternatively, optimising the muck removal process, such as deploying additional or more efficient disposal equipment, could also help enhance overall productivity.

## 9 ANALYSIS

### 9.1 Time and Manpower Savings

In the case of the N109A project, the RPJM method resulted in significant time and manpower savings. Specifically, it saved 50% of manpower hours and reduced the construction period by 4 months.

Similarly, the RPJM method was used in other projects, such as T221 (Havelock MRT Station), to construct their linkways. In T221, the RPJM method achieved a 30% improved productivity (Foo, 2017).

### 9.2 Soil Conditions and Site Constraints

The RPJM method has been successfully deployed in various soil conditions across multiple projects, showcasing its versatility and effectiveness in different environments.

Table 5. Project Comparison (Lu, n.d) (Ng, 2017)

Project	Geology	Under Passing	Overburden
N109A	Bukit Timah Granite (Residual Soil)	Live Roads and Utilities	7m
Funan	Kallang Formation (Marine Clay)	Live Roads and Utilities	3.6m
T221	Bukit Timah Granite (Residual Soil)	Live Roads and Utilities	5.45m

### 9.3 Others

Table 6. Pros and Cons of RPJM and Cut and Cover Method

Parameters	RPJM	Cut and Cover
Construction Time	Shorter Time	Longer Time
Traffic Diversion	Not required	Required
Utility Diversion / Support	Not required	Required
Environmental Impact	Low	High
Manpower	Less manpower	High manpower
Heavy Machinery	Less	Many

Parameters	RPJM	Cut and Cover
Safety	Lower Risk	Higher Risk
Cost	Higher	Lower
Linkway Customisation	Straight	Customisable

## 10 CONCLUSION

In conclusion, the RPJM method has proven to be highly successful in the construction of the first linkway in N109A, with Linkway 2 completed and Linkway 1 now preparing for the same approach. While there is always room for further improvement, the evolution of RPJM from its initial use in Funan to its current implementation in N109A demonstrates the method's ongoing progress and adaptability.

The comparison between RPJM and traditional cut-and-cover methods reveals the significant advantages of RPJM. Despite higher costs and some limitations in the customizability of linkway sizes and shapes, RPJM offers remarkable benefits in terms of time savings, reduced complexity, minimal environmental impact, and enhanced safety. These benefits make RPJM a highly efficient and productive option for underground linkway construction.

This has been demonstrated in successful projects such as Funan, T221, and N109A, where RPJM has continued to shine in terms of efficiency and productivity. With its proven success and continuous improvements, RPJM is poised for wider recognition and adoption in the construction industry. The future of underground linkway construction looks promising, with RPJM leading the way in transforming construction processes to be more innovative, efficient, and sustainable.

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