A Technical Overview of Contract No. 3801 APM and BHS Tunnels on Existing Airport Island: Jacked Box Tunnels under AEL

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doi: https://doi.org/10.21467/proceedings.159.13

ABSTRACT

The provision of the new Automated People Mover (APM) tunnel connecting the expanded Terminal 2 (T2) with the Third Runway Concourse (TRC) and the new Baggage Handling System (BHS) tunnel, are key works being provided as part of the expansion of the Hong Kong International Airport (HKIA) into a Three-Runway System (3RS).The alignment of the tunnels crosses under the operational Airport Express Line (AEL) and was constructed using Jack Box tunnelling techniques. This paper presents some of the technical solutions developed for the box jacking works. Two 30m long portions of the APM and BHS tunnels were jacked as continuous precast reinforced concrete boxes under the AEL embankment within a ground improved grout block. A horizontal pipe pile canopy positioned above the tunnels was constructed using micro TBM methods to allow ground movement control and enhance face stability. The two boxes were jacked forward off a jacking slab using hydraulic jacks positioned at the rear of the boxes. An additional innovative strand jacking system was employed in combination with the canopy piles as an anti-drag system, which also supplemented the slab jacks thrust. The thrust forces on the post-tensioned prestressed jacking slab were restrained by a combination of rock friction and inclined temporary ground anchors. The two boxes were safely jacked to their final position in July 2022 without disrupting MTRC AEL operations.

Keywords: Box jacking, Ground Improvement, Rail protection

1 Introduction

1.1 General

The new APM and BHS tunnels have an approximate length of 2.6km and will run between HKIA's T2 and the Third Runway Concourse (TRC) buildings. The two tunnels are vital for the successful operation of the TRC as part of the 3RS development. The section of the tunnels formed within the existing HKIA platform from the expanded T2 to the TRC which is within the newly reclaimed 3RS platform are being constructed under Contract No. 3801 (C3801). The portion of the proposed tunnels that cross under the operational AEL were constructed using Jack Box tunnelling techniques (Figure 11). Using this technique two pre-cast concrete boxes were built in a casting and jacking shaft on the south side of the AEL embankment and jacked through the embankment into a receiving shaft on the north side, whilst maintaining the operation of the AEL railway.

China State Construction Engineering Ltd (CSCE) is the Main Contractor of the works and Intrafor Ltd (ITF) is the Specialist Contractor for the Jacked Box construction. ITF was responsible for a) the ground improvement works; b) the temporary structures for the launching and jacking of the boxes; c) the structural design of the boxes in all the temporary conditions and temporary loads; and d) the

Proceedings DOI: 10.21467/proceedings.159; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-965621-6-8

construction of the two reinforced concrete boxes. ITF engaged AECOM's (AEC) legacy company, Benaim Ltd, to provide the detailed design of the box jacking works. CSCE-ITF-AEC teamed up for the second time in similar roles to successfully execute the box jacking works under C 3801, following the previous box jacking works of HKLR03 at Scenic Hill (Cook *et al.*, 2018). ITF-AEC having also worked together on the award-winning Brisbane Airport Link jacked tunnels at Toombul in Australia. The main parties involved in the C3801 project are presented in Figure 12.

Figure 11: *C3801 – Project area*

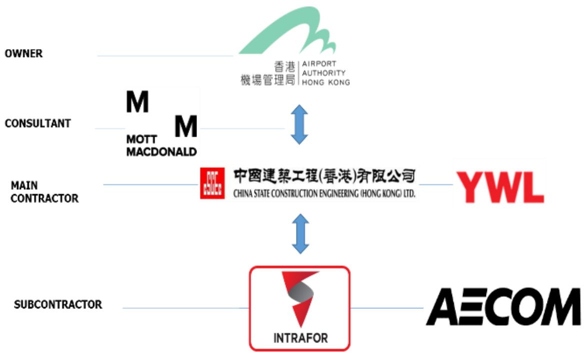

Figure 12: *C3801 – Project O-chart*

1.2 Structures and Construction Concept

The two permanent reinforced concrete boxes were jacked through the ground below the AEL railway well below natural groundwater level, which was tidally affected. The jacking length for both boxes was approximately 30m. Each of the two boxes were monolithically constructed as single units with an approximate length of 30m. The boxes are oversized outside their original curved alignment envelope to allow their jacking along a horizontal plane and on a straight line.

To accommodate the construction (temporary) stage the APM box had cross sectional dimensions of approximately 30.9m wide by 9.4m high and a length of 30m - (Figure 13 and Figure 14). The BHS box has cross sectional dimensions of approximately 19.8m wide by 11.8m high and a length of 30m.

The front of both jacked boxes was inclined at 70 degrees from the horizontal and were equipped with a steel shield at the wall interfaces with the ground faces.

In order to enable the construction of the two jacked boxes, two temporary shafts were constructed (see Figure 11). The shaft on the southern side of the AEL embankment, was the casting and jacking shaft. The shaft on the northern side was the receiving shaft. Once formation level was reached inside the jacking shaft, the jacking slab (Figure 6) was constructed. This served initially as the casting bed for the two boxes and subsequently as the reaction system for the jacking works, transferring the jacking loads to the ground only, ensuring no load transfer to the ELS of the shafts as required under the contract Each tunnel box was precast inside the jacking shaft, providing a higher quality of works compared to casting the tunnel in-situ beneath the AEL. The boxes were then jacked forward off the casting bed (the jacking slab) using push jacks located at the rear of the boxes which reacted against corbels stressed down to the jacking slab.

The maximum depth of overburden over the BHS box is approximately 8.5m and for the APM it is approximately 9m. The original embankment for the AEL was constructed with rockfill. Grouting of the fill material was carried out using fan array methods from the sides and extending under the AEL. The ground improvement works were an essential part of the Box Jacking works to provide a hydraulic cut-off from the tidally affected groundwater under the AEL; improve the ground properties like mass stiffness, strength and permeability; as well as limit ground settlements; and ensure face stability during excavation and jacking operations.

To provide groundwater cut-off two grout walls made by the Tube a Manchette method (TAM) were formed along the external edges of the tunnels extending from the design ground water level at +3.5mPD down to the toe which was embedded into the underlying rockhead, providing - together with the grouted cofferdam walls for the jacking and receiving shaft installed by CSCE - a sealed enclosure of the site.. The shafts perimeter grout curtains were supplemented by a mass fan grouting array pattern, extending from the jacking shaft to the receiving shaft, in order to:

a) limit ground movements during box jacking;

b) provide excavation face stability; and

c) stabilise any residual water bearing ground.

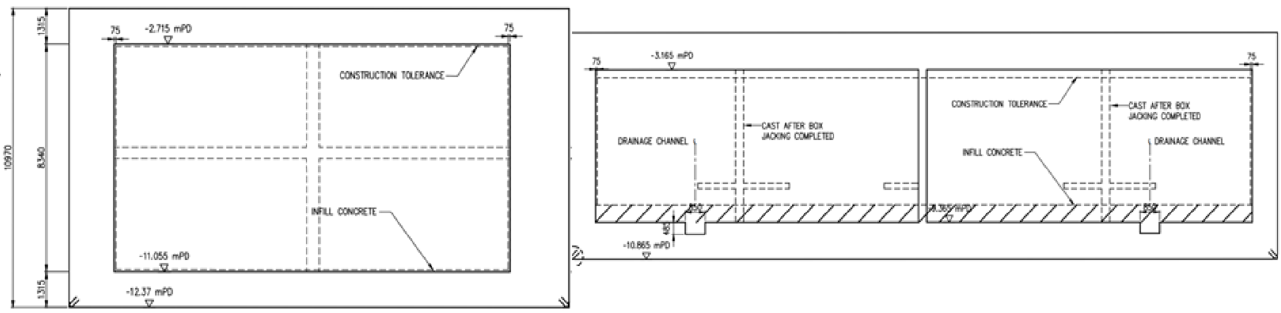

Figure 13: *Typical Sections of APM & BHS Boxes*

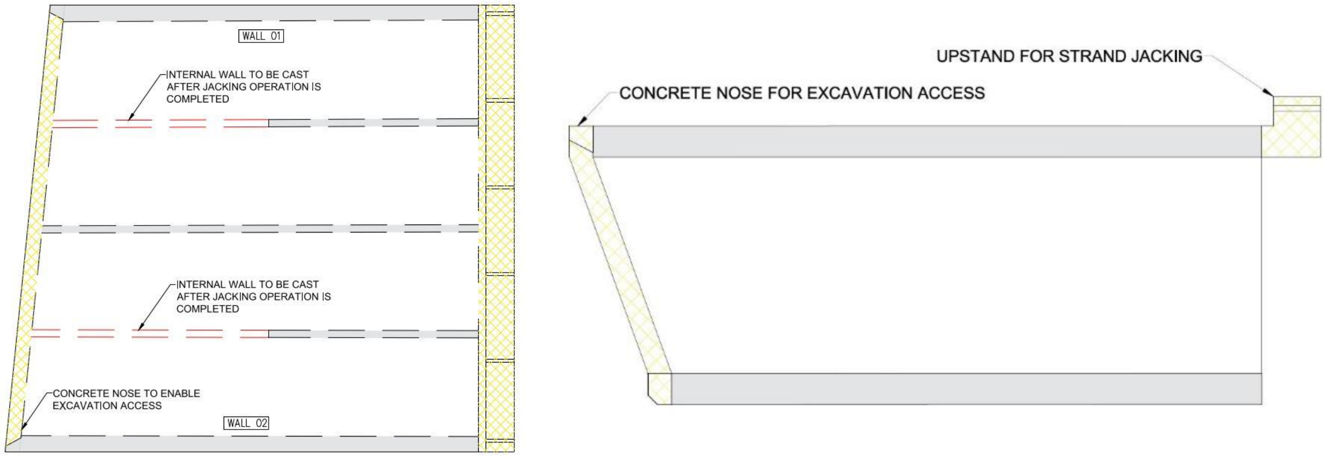

Figure 14: *Plan View and elevation of APM & BHS Boxes*

To enable the construction of the two jacked boxes, two temporary shafts were constructed by CSCE (see Figure 15). The shaft on the southern side of the AEL embankment was the casting and jacking shaft, while the one on the northern side was the receiving shaft. The shafts were approximately 20m deep on the BHS side and 18.5m deep on the APM side. The two shafts were formed using steel pipe piles which were supported mainly by a braced steelwork excavation and lateral support system, except for the headwall where the braced steelwork was designed out. This latter arrangement allowing the jacked boxes to enter the embankment through the pipe piles which were incrementally demolished as the boxes entered the embankment. Once formation level was reached inside the jacking shaft, the jacking slab (Figure **16**) was constructed, which served initially as the casting bed for the two boxes and subsequently as the reaction system for the jacking works, transferring the jacking loads to the ground ensuring no load transfer to the ELS of the shafts by providing a sliding interface along the side faces of the jacking slab

The mass grouting under the AEL displaced the groundwater from the rockfill. This was confirmed via horizontal probing from the shafts before the headwall removal.

To limit potential AEL movements and provide excavation face stability, a pipe pile canopy was constructed prior to excavation/jacking operations. The horizontal steel pipe piles was formed using 1430mm diameter steel pipe, installed by micro TBM and then infilled with grout. These pipes extended from the jacking shaft to the receiving shaft. The canopy also acted as an anti-drag system (ADS) isolating the embankment over the boxes from horizontal displacement effects caused by the box friction under as it moved forward. The pipes themselves being restrained by prestressing strand that passed through the duct in the centre of the grouted pipes to strand jack attachment points on the top rear of the boxes. Excavation of the ground was then carried out in 1.5m steps under the canopy, followed by incremental jacking of the tunnel boxes.

An extensive instrumentation and monitoring plan was provided. This included a real time Automatic Data Monitoring System (ADMS) with instrumentation and monitoring “Alert”, “Alarm” and “Action” limits for the AEL rail tracks. Vertical track movement (settlement and heave), horizontal movement, differential settlement between rails, as well as vibration were recorded and reported in real time, enabling any transgressions of AAA levels to be automatically notified to the relevant parties by SMS and email.

Proceedings DOI: 10.21467/proceedings.159
ISBN: 978-81-965621-6-8

Series: AIJR Proceedings
ISSN: 2582-3922

1.3 Main Site Constraints

The main site constraints of the project can be summarised as follow: (i) the MTRC AEL, whose regulations govern the maximum allowable ground settlement and vibrations induced by the construction activities; (ii) working restrictions due to the close proximity to AEL; (iii) existing utilities within the AEL embankment such as a fresh water main, CLP cable ducts, communication cables and a storm water drain; (v) king posts at the back of the jacking shaft supporting the temporary traffic deck which extended partially over the site; (vi) the heavy braced steelwork that provided the ELS for the jacking and receiving shafts (see Figure 11).

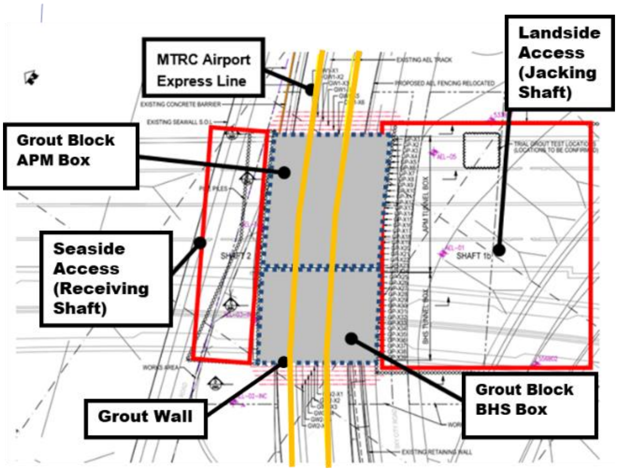

Figure 15: *Footprint of Receiving and Jacking Shafts*

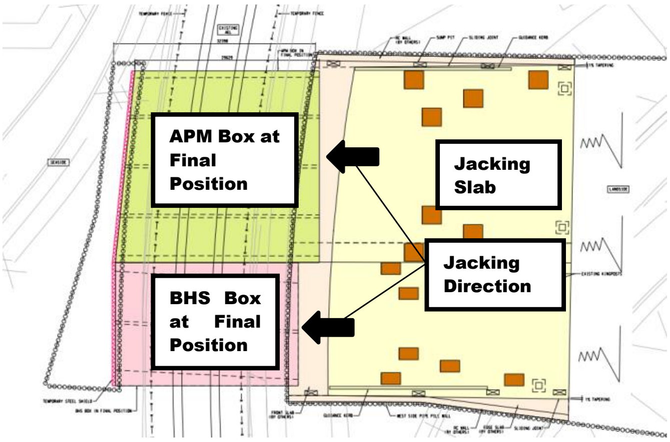

Figure 16: *General Plan of Box Jacking Works*

2 Grout Block Under AEL (GBUAEL)

2.1 In-Situ Ground Conditions

The in-situ ground conditions of the project area comprised rockfill, overlying alluvial sand lenses and saprolitic decomposed granite. The rockfill was placed during the original reclamation works for the Chep Lap Kok Airport platform and is composed of boulders, cobbles and sand. The depth of rockfill under the AEL embankment varies between 17m and 20m. The underlying granite rockhead varies significantly and generally lies between 5m and 25m lower than the final formation level of the jacking slab.

2.2 Ground Improvement Scheme - Objective

An essential element of the Box Jacking Works was the successful implementation of ground improvement over the tunnel works site zone under the AEL. To ensure the safe execution of the works and the continued safe operation of the AEL it was necessary to enhance the engineering properties of the in-situ ground. The ground improvement works aimed to enhance the following ground properties:-

a) Mass stiffness - for the control of ground deformations induced by the works and therefore limit the resulting ground settlement movements under the AEL;

b) Strength - to improve face stability during excavation underneath the AEL as well as to reduce the horizontal earth pressure imposed on the headwalls of the jacking & receiving shafts; and

c) Permeability - to control groundwater seepage into the works and the potential for adverse consolidation effects due to drawdown of the naturally occurring levels.

The target strength and stiffness properties are presented in Table 4.

Table 4: *Target properties for GBUAEL*

Engineering Property	Target Value
Friction Angle (ϕ')	40° (min)
Cohesion (c')	50 kPa (min)
Young's Modulus (E')	250,000 kPa (min)
Permeability (k)	1 x 10^{-6} m/s (max)

2.3 Grout Trial Block (GTRB)

For this project two trial grout blocks (TR1 and TR2) had to be formed within the Island reclamation fill at a location where they best represented the ground conditions of the future GBUAEL (see Figure 17). The testing of these GTRB was used to demonstrate the grouting quality and to verify whether the design parameters specified in the detail design were achievable before the actual grout block works under the AEL were carried out.

The GTRB were formed using permeation grouting inside of a 7.0m x 7.0m cofferdam, which was made of steel pipe piles and a grout curtain to provide a hydraulic cut off and prevent seepage below the toe of the wall. The same grouting technique was employed as for the future GBUAEL. The grout holes were done vertical with a spacing of 1.3 x 1.5m.

The same verifications tests as for the main GBUAEL had to be carried out for the trials and included: (i) Geophysical Testing to confirm the integrity of the GTRB; (ii) Plate Load Tests to confirm the Young Modulus; (iii) Angle of Response; (iv) Falling Head Tests to verify the permeability; and (v) Pressuremeter Tests to confirm the target soil properties.

Both the TR1 and TR2 confirmed that the trial grouted soil parameters met the specified target design criteria used for the detail design of the main GBUAEL.

2.4 Ground Improvement Scheme - Implementation

Firstly, the Tube a Manchette (TAM) grouted cofferdam walls for the jacking shaft and the receiving shaft were constructed. Two further grout walls were then constructed (Figure 19), one on each side of the AEL, with toe embedment into the underlying rockhead. These two grout walls provided a sealed enclosure to the site by connecting with the TAM grouted headwalls of the jacking shaft and receiving shafts. A Grout Block under the AEL was then formed within this sealed enclosure by permeation grouting. The extent of the grouting works was sufficient to effectively form 'sidewalls' to the tunnels and control the potential for lateral movements at the excavation face during the jacking/excavation works.

The grouting technique and the sequence of grouting were developed to maximise control over/limit near-surface ground movements and hence AEL impacts. The technique was detailed to ensure that the installation could be carried with a fan of inclined boreholes from outside the proposed fence line of the MTRC boundary (3m buffer from AEL) and protect the adjacent utilities in the area. The treating of similar ground by permeation grouting was previously successfully used on the Scenic Hill jack box (Cook *et al* 2018).

2.5 Ground Improvement Scheme – As Built Verification

After completion of the grouting works, the following verification tests were carried out for the grout block (see):

1) 30No. constant head tests through 10No. vertical boreholes to establish the permeability;
2) 50No. pressuremeter tests through 10No. inclined boreholes for verification of the Young's Modulus and back analysis of the shear strength; and

Proceedings DOI: 10.21467/proceedings.159
ISBN: 978-81-965621-6-8

Series: AIJR Proceedings
ISSN: 2582-3922

3) Geophysical tests (cross hole seismic test) through 10No. vertical boreholes to establish the integrity of the grout block.

Based on the verification test results the minimum measured permeability of the GBUAEL was 9.2x10-7m/s, the minimum Young's modulus was 264MPa and the minimum cohesion was 217kPa. These minimum values were higher than the target properties. In addition the geophysical testing results measured wave velocity within each formation (rockfill, alluvium and CDG) indicated that the grouting works met the design intent within all formations.

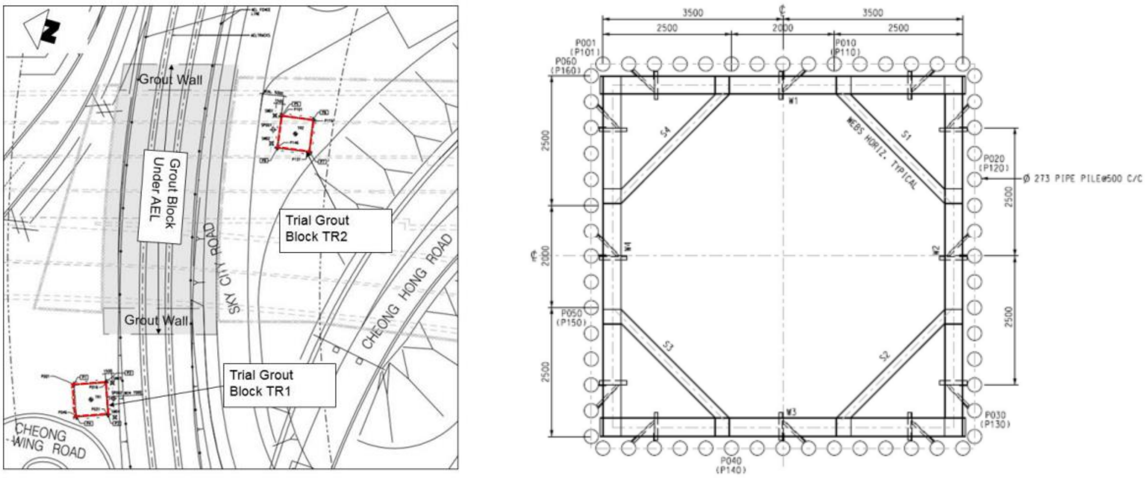

Figure 17: *Location and cofferdam of Grout Trial Block (GTRB) TR1 and T2*

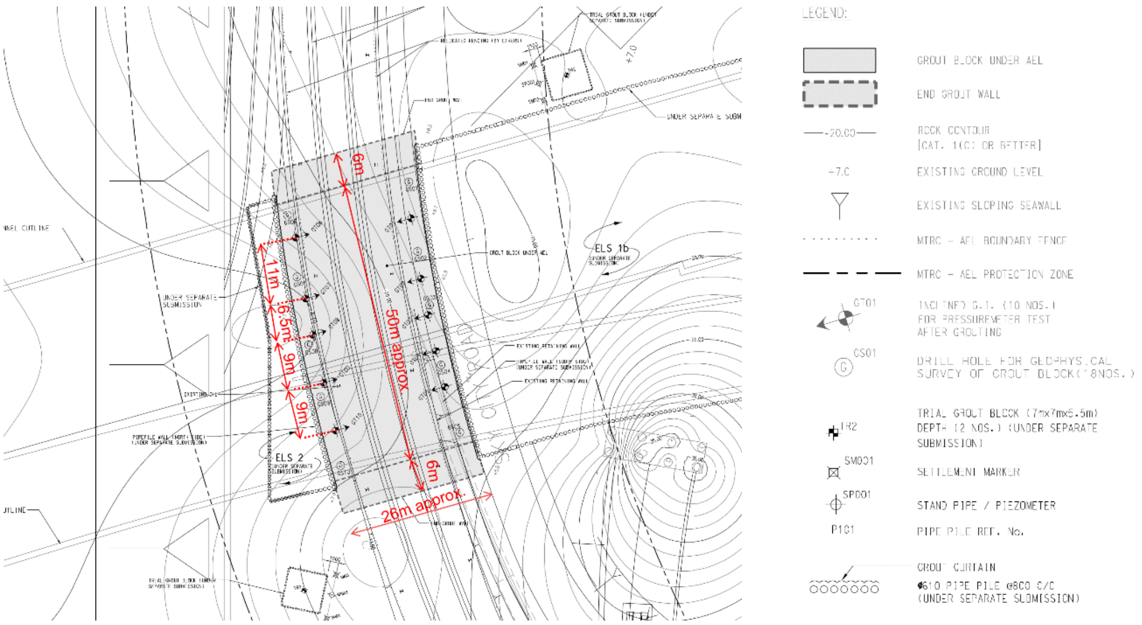

Figure 18: *Layout of the executed GBUAEL verification test program*

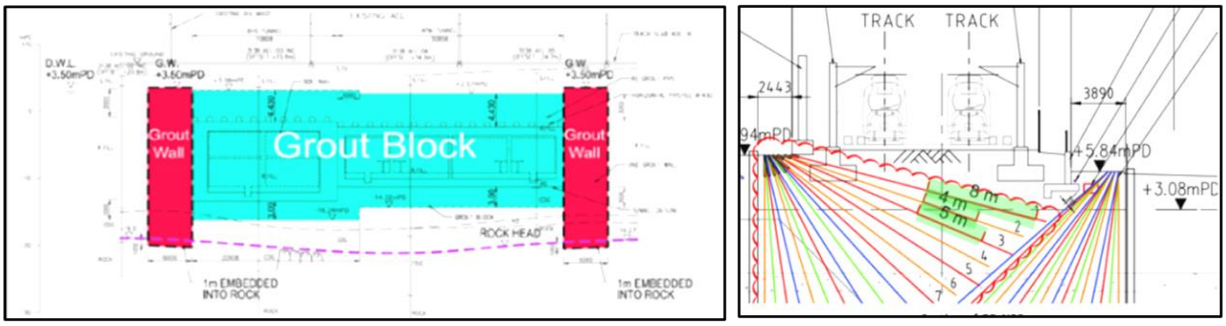

Figure 19: *a) Cross section Grout Walls and GBUAEL;* *b) Typical Fan Grouting Section under AEL*

3 Horizontal pipe piles (HPP)

3.1 HPP Requirements

Grouted HPP were used to form a canopy above the crown of the APM and BHS jacked boxes, these being restrained by horizontal prestressing strands placed within centrally positioned ducts which were attached to the top rear of the boxes. The HPP were made of 1430mm diameter x 14mm thick spirally welded steel pipes spaced at 2.0m centres. The canopy was a fundamental element of the temporary works used to control ground settlements during the excavation process. The HPP provided a stiff support to the AEL embankment as they span over the excavation face, supported off the jacked box on one side and off the improved ground ahead of the excavation face on the other side.

The restrained HPP also provided the controlled sliding surface for the crown of the reinforced concrete tunnel boxes by acting as an Anti-Drag System (ADS), thus isolating/preventing horizontal ground disturbances of the AEL embankment during the jacking works.

3.2 Installation of HPP

The 26 No. HPP were installed by pipe jacking and using micro TBM's, from an intermediate formation level above the crown of each tunnel box, in advance of the jacking and receiving shafts being excavated down to their formation level (see Figure 20). The pipes were delivered in stock lengths of 6m. At the joint interface of the connecting pipe lengths a flexible temporary joint connection using a rubber seal was provided to enable a smooth control of the alignment and level. The flexible joint connection was then welded with a full butt weld after the pipe in front of the joint was fully jacked into the ground, finally forming a continuous pipe from the jacking shaft to the receiving shaft. The jacking works were typically carried out during MTRC's non-operation hours, while the welding works was done during the day off the programme critical path.

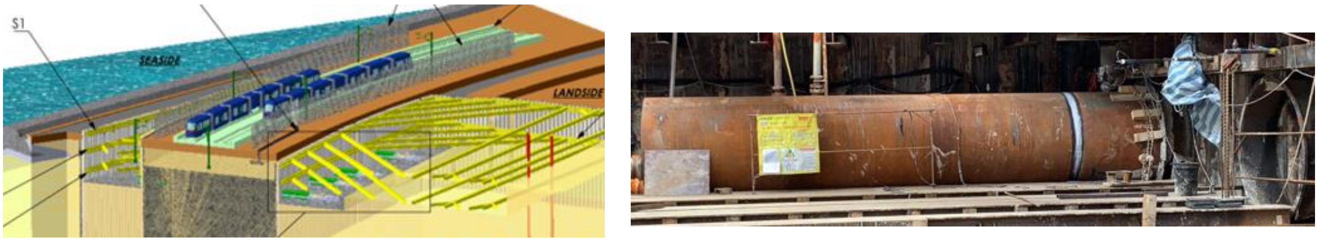

Figure 20: *Installation of Canopy Tubes above Crown of Tunnel Boxes by micro TBM and pipe jacking*

The micro TBM enabled the installation of the pipes to close tolerances in alignment and level, well within the specified +/- 100mm. The pipe jacks were secured to a temporary reaction slab and wall to resist the TBM thrust forces.

After completion of installation of a respective tube, annular grouting was carried out, where the periphery of the tube was grouted over its full length. After jacking of all HPP, the tubes were filled with grout around the central placed prestressing ducts.

4 Box jacking System

4.1 The Jacking Slab

Once formation level was reached inside the launch shaft, the jacking slab with its shear keys and inclined anchors(see Figure 21) was constructed, which initially served as the casting bed for the two jacked boxes, and subsequently as the reaction system that enabled the jacking of the tunnel boxes, without loading the shaft ELS.

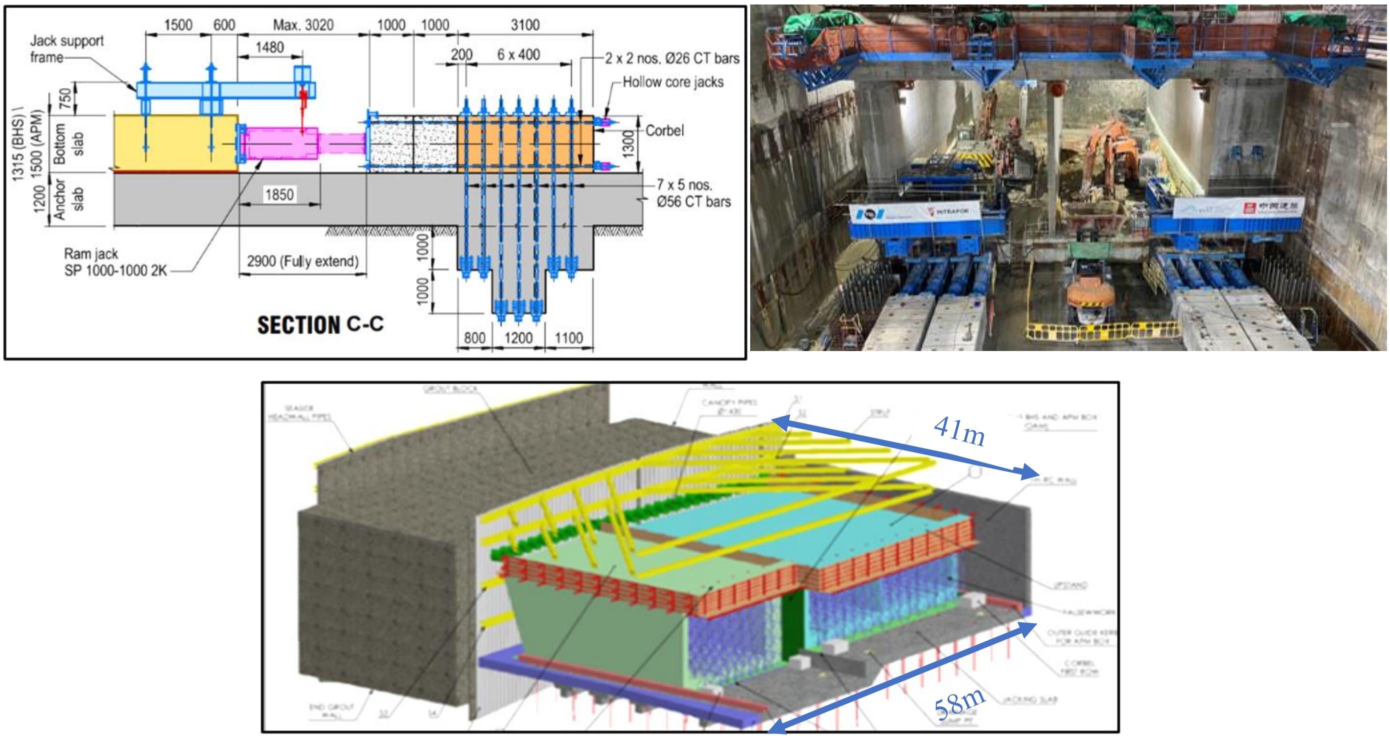

Figure 21: *Construction of APM and BHS Tunnel Boxes in Jacking Shaft on top of Jacking Slab*

The jacking slab was a 1.2m thick post-tensioned raft with four shear keys of 2.0m depth, anchored to grade III rock with temporary ground anchors. The structurally monolithic slab was formed with two terrace levels to accommodate the different soffit levels of BHS box (top of slab -12.373mPD) and APM box (top slab -10.868mPD). For each level the surface is flat without any longitudinal gradient or crossfall. The jacking slab is separated by a movement joint from the edge infill slabs around the vertical pipe-pile wall. The movement joints along the sides were designed as sliding joints with sliding bearings at the interface, to prevent on the one hand any shear transfer to the ELS system, but also on the other hand to provide axial support to the vertical PP wall to enable the removal of the lower strutting levels S3 and S4 which would otherwise clash with the boxes construction. Towards the headwall the jacking slab was separated by the provision of an infill slab, which acted as a horizontal deep beam to provide support to the headwall, the jacking slab being isolated from it by a 20mm joint with a compressible joint filler, but with dowel bars to prevent differentials developing across the infill/jacking slab sliding surfaces.

Concrete guide kerbs designed for accidental skew loadings were cast on top of the slab on the outer side of the BHS and APM boxes to guide the boxes during the jack boxing operation.

Each tunnel box was cast inside the launch shaft on the jacking slab (Figure 21). This ensured a safer and higher quality of works compared to casting the tunnel in-situ beneath the AEL, in the multiple stages, that would otherwise be required. In order to provide sufficient space for an excavator, the central internal wall and slab of the BHS box as well as the front part of the two outer internal walls of the APM box were omitted for the 1st stage and cast in a 2nd stage after completion of the box jacking operations (refer to Figure 14). The boxes were then jacked forward off the jacking slab (casting bed) using ram jacks located at the rear of the boxes (which jacks reacted against corbels attached to the jacking slab by tensioned stress bars).

The tunnel boxes were jacked forward across the jacking slab, spacer blocks being installed in between the tunnel boxes and corbels iteratively to fill the gap as the tunnel boxes were being jacked forward. The jacking force being transferred through the spacer blocks to the restraining corbels, and then to the shear keys and inclined anchors underneath. The anchors were embedded in CDG strata and rock strata below the jacking slab invert.

The jacking at the rear of the tunnel boxes was carried out by up to 3000mm stroke jacks with 460 tonne working loads and supplemented with short stroke ram-jacks of 2000 tonne working loads (Figure 23). The jacks were equipped with a spherical head at either end to allow some bearing geometry tolerance and were supported on a cantilevering steel hanger frame fixed to the bottom slab of the tunnel boxes. The jacks applied the forces to embedded steel plates cast into the rear of the box base plate (see Figure 22).

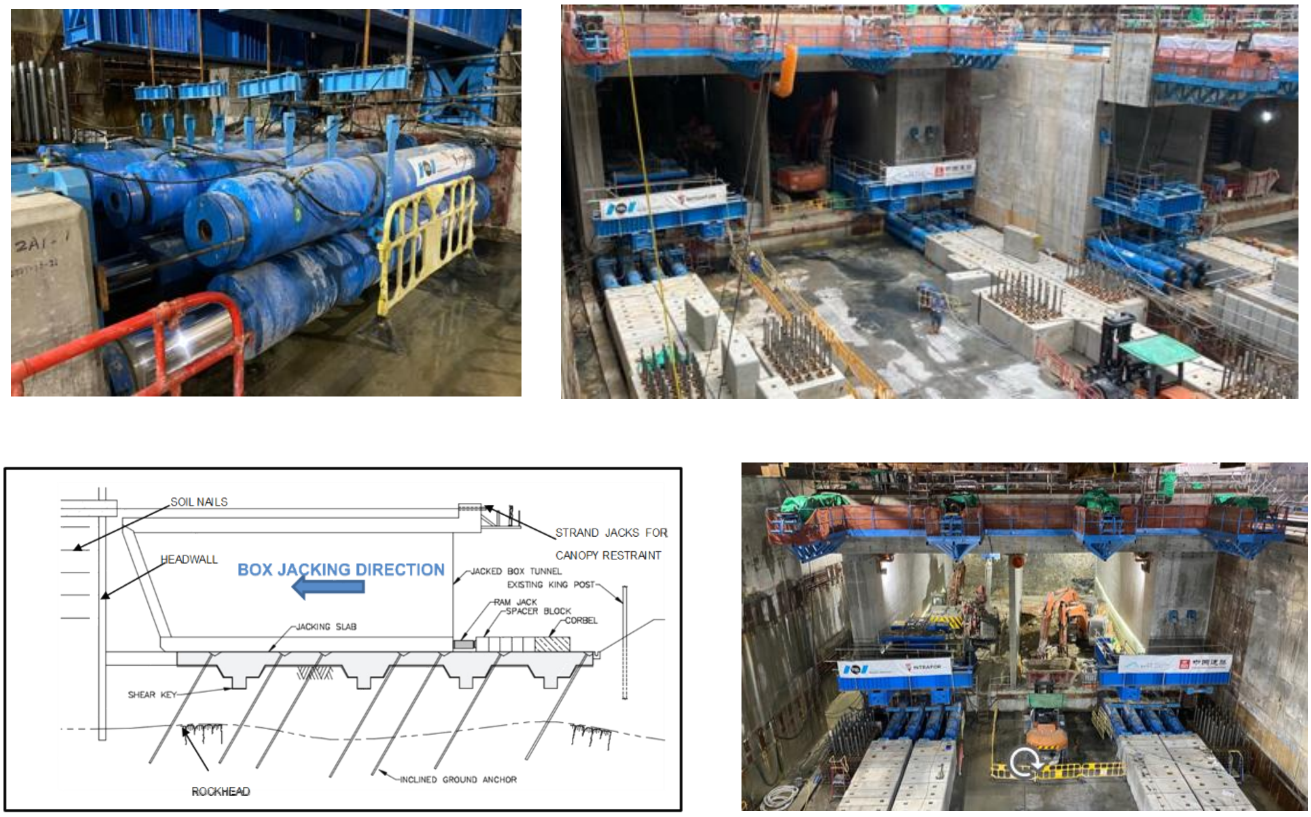

Figure 22: *Typical Arrangement of Jacked Boxes on Jacking Slab*

The required jacking forces to overcome the friction between the tunnel box and the surrounding interfaces was estimated by carrying out a sensitivity analysis using upper and lower bounds for the materials present and by considering a bentonite lubrication system to reduce the friction during jacking. “Best estimate” serviceability friction forces were estimated which were multiplied by a 1.5 safety factor to derive the “design” jacking forces. The provided total jacking capacity which was allowed for was significantly higher than the estimated design friction forces, to allow for unforeseen geotechnical variations. The highest jacking forces occurred typically during break out of a respective jacking stage, after which the forces gradually decreased as the box began moving (ref Table 2).

Table 5: *Summary of estimated versus actual jacking forces*

Box	Best Estimate [MN]	FoS	Design Friction [MN]	Strand Jack Capacity [MN]	Ram Jack Capacity [MN]	Total Jack Capacity [MN]	Max Actual Jacking Force [MN]
APM	141	1.5	212	48	175.5	223.5	192
BHS	95	1.5	142	32	114	146	101

Prestressed ground anchors were installed prior to the box jacking operation at angle of 30 degrees to the vertical. The horizontal component of the anchors prestressing force being detailed so as to act against the jacking force during box jacking operations. The vertical downward force component of the ground anchors also acting as a surcharge on the soil underneath the slab enhancing the horizontal friction shear resistance. The jacking slab relied on the horizontal component of the ground anchor prestress force, as well as the soil friction under the slab and at the toes of the shear keys, to resist the horizontal jacking force during box jacking operations (Figure 24). While the horizontal anchor force and soil friction provided the primary restraint during jacking, before significant movement occurred, the passive resistance behind the shear keys was also assessed to understand the ultimate stability FOS against failure. Notwithstanding the system strain compatibility differences between these restraint types.

The above ultimate potential failure checks were undertaken first as a global stability check. Detailed checking was also undertaken using Plaxis, which allows soil/structure rigorous analysis to assess the potential of local failures, as well as the level of ground deformations/structure movements during jacking. Conventional 2-D Plaxis was first used for this assessment to comply with the expectations of the Approval Authorities.

A 3-D analysis with Plaxis 3-D was then additionally undertaken to assess the stability of the jacking slab and the induced deformation in a more realistic way (Figure 25). In addition, the 3-D analysis enabled a more accurate model of the distribution of the stress around the corbels during jacking, and hence the induced ground movements. In addition, the 3-D model enabled the assessment of the interaction between the jacking slab and the ELS system of the launching shaft through the ground. Finally, the 3-D model allowed the impact of the jacking works on the adjacent king post supports (which were supporting the temporary bridge structures over the sire) to be assessed, which supports passed through and adjacent to the jacking slab.

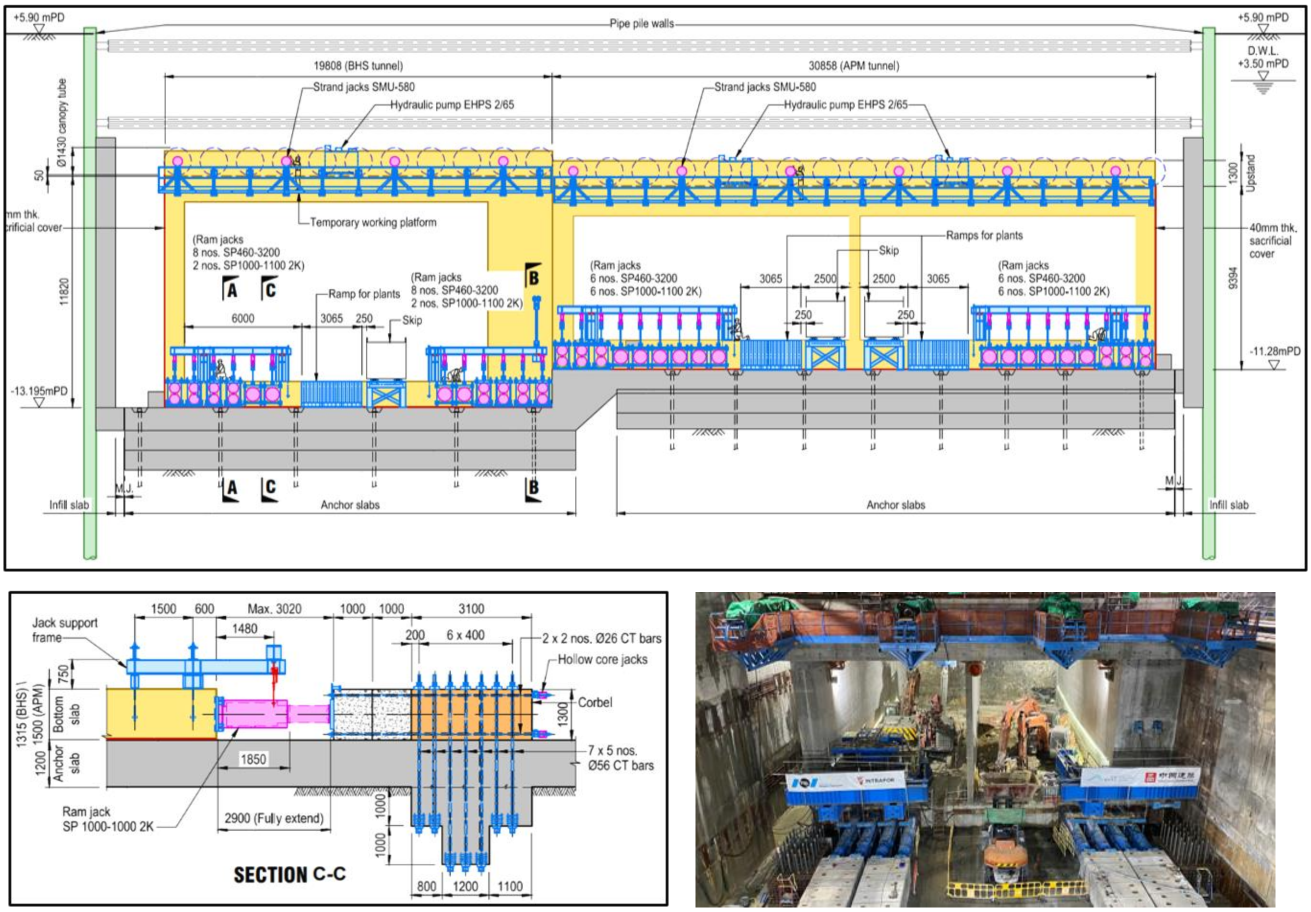

Figure 23: *Typical Arrangement of push jacks at rear of APM and BHS box*

4.2 Monitoring of the jacking slab and the AAA levels system that were adopted during the works.

The maximum horizontal displacement limit of the slab parallel to the jacking direction was set to only 10mm while the lateral ground deformation limits to be measured using inclinometers were ±7mm. These values were also defined as 'Alarm' values. Despite the fact the Alarm values were stringent, the monitoring of the relevant instruments did not breach them. The relevant values assessed in Plaxis 2-D were more than 50% higher than the limits adopted in construction. However the movement assessment using Plaxis 3-D showed lower limits could be achieved and thus allowed lower limits to be adopted with confidence that they would be achieved in practice. In other words the 3-D method of analysis contributed towards safety during the works, by allowing the setting of a lower allowable deformation.

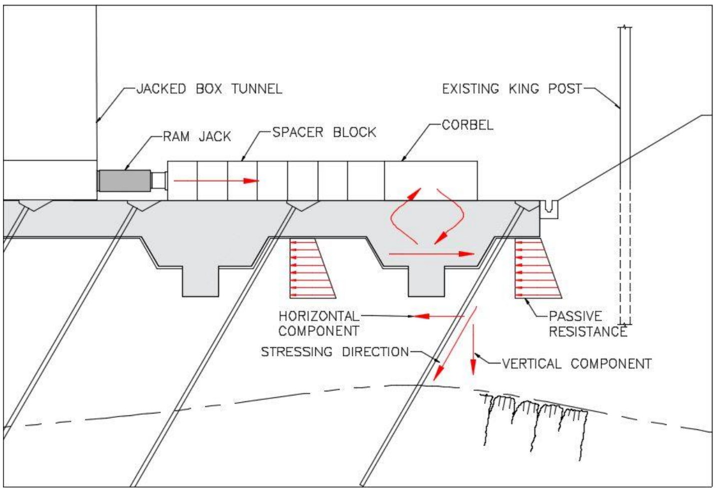

Figure 24: *Jacking slab restraint load considerations*

4.3 Ground Anchors Design

The ground anchors used to restrain the jacking slab were a single proprietary 14No. strand temporary ground anchor type with a working load of 2300kN. **Error! Reference source not found.** presents the t ypical arrangement of the ground anchors while Table 3 provides the properties of the anchors. The ground anchors had a minimum free length of 4m and were anchored in rock, grade III ore higher with a minimum fixed length of 3m excluding the sump section. The strands were PE sheathed within their free length and bare within the bonded length and ran inside a corrugated PE duct. The design of the anchors was in accordance with BS8580 (latest version) which is also in accordance with Hong Kong's own GEOSPEC 1. The design specifications of the anchors were set to comply with the most up to date definition of loads to comply with BS8580. The design effort put into this allowed the contractor to conduct an anchor test program which was rigorous and complied with the state of the art technical requirements for prestressed ground anchors. Three suitability ground anchor tests had to be carried out in advance of the installation of the working ground anchors under the identical conditions and configuration. These suitability tests were carried out from the HPP formation level behind the temporary reaction slab for the canopy tube jacking (Figure 26).

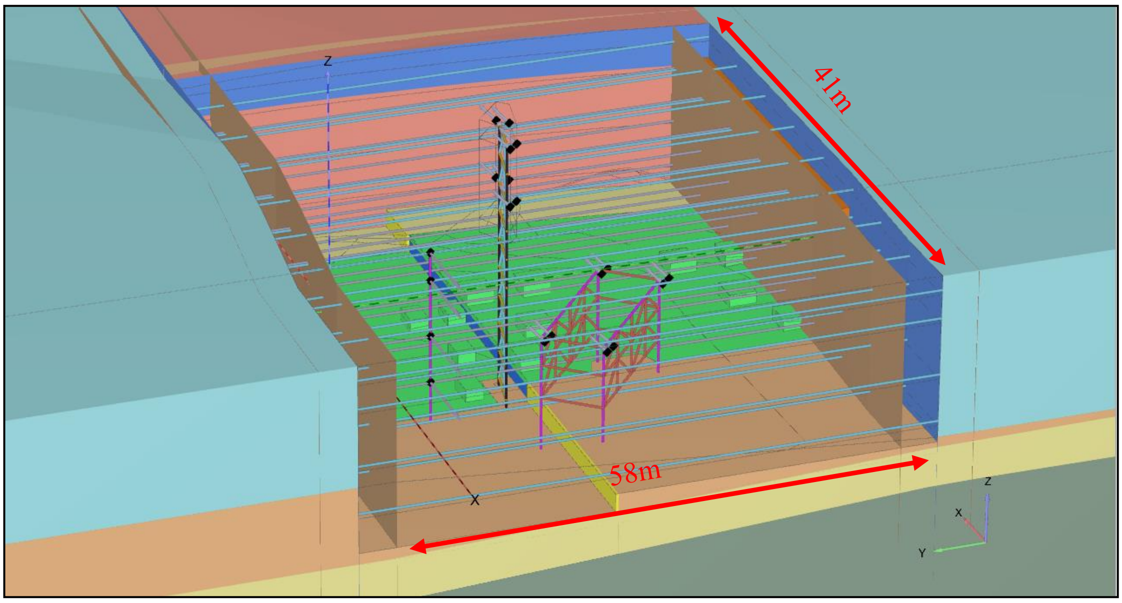

Figure 25: *Plaxis 3-D model for the analysis of the jacking slab*

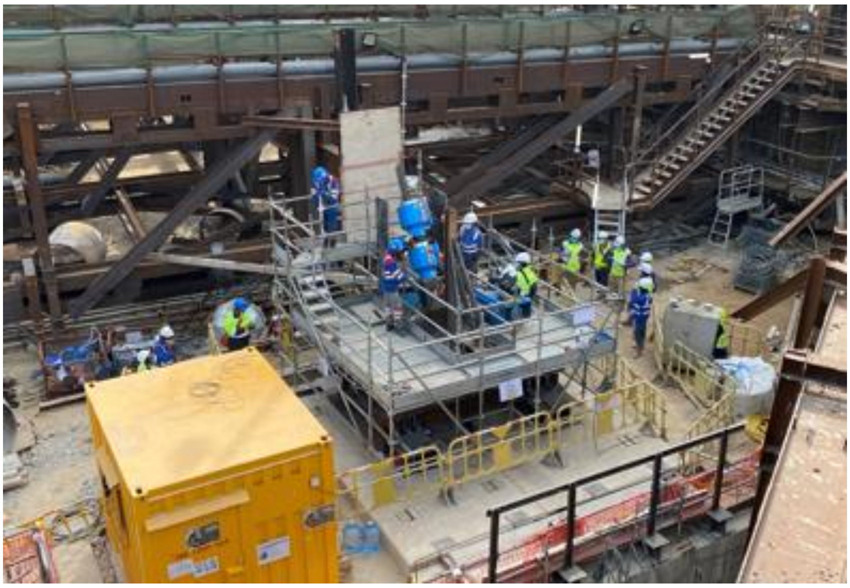

Figure 26: *Ground Anchor Suitability Test Set Up*

4.4 Load Paths

As noted above the friction forces acting at the sliding interface between the roof slab and the HPP were restrained by a strand jacking system attached to the top rear of the boxes (refer to the Anti-Drag System section).

The ram-jack forces were reacted by the jacking slab and the soil / structure interaction that transmitted the forces into the ground mass below the slab formation. The ram jack forces entered the slab via the thrust corbels that were positioned at discrete locations on the jacking slab to suit the ram-jack arrangement. The slab acted as a horizontal diaphragm to transmit the thrust loads to the shear keys while resisting the out of plane bending and tension effects these induced.

Table 3: *Properties of Proposed Ground Anchors*

S/N	Description	Value
1	Working Load	2300 kN
2	No. of Strands per Anchor	14
3	Strand Diameter	15.7mm
4	Ultimate Breaking Load of Anchors	3906kN
5	Minimum Free Length	4000mm
6	Minimum Fixed Body Length	3000mm

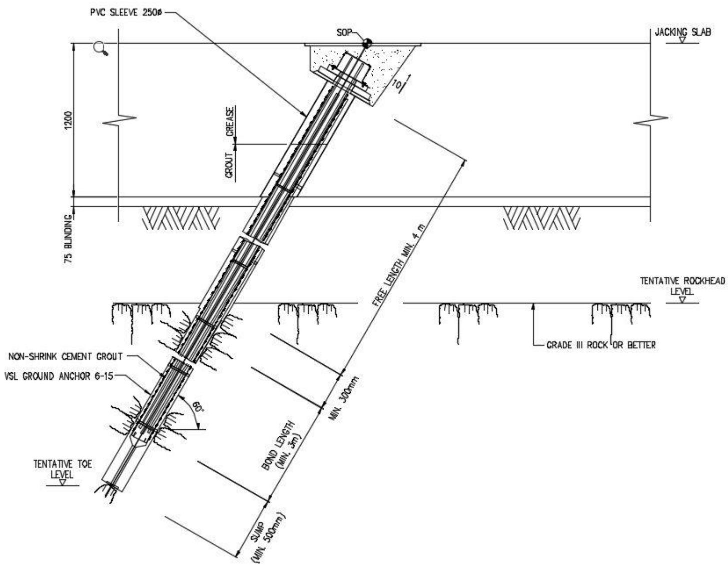

Figure 27: *Typical Arrangement of Inclined Ground Anchor*

The shear keys transmitted the thrust loads into the upper sections of the formation by inducing a passive reaction locally in the ground (Figure 28). The horizontal component of the prestressed 30 degrees inclined temporary ground anchors (Figure 17) acted against the jacking force, while the vertical downwards component acted as a surcharge on the soil and thus increased the soil interface shear friction resistance.

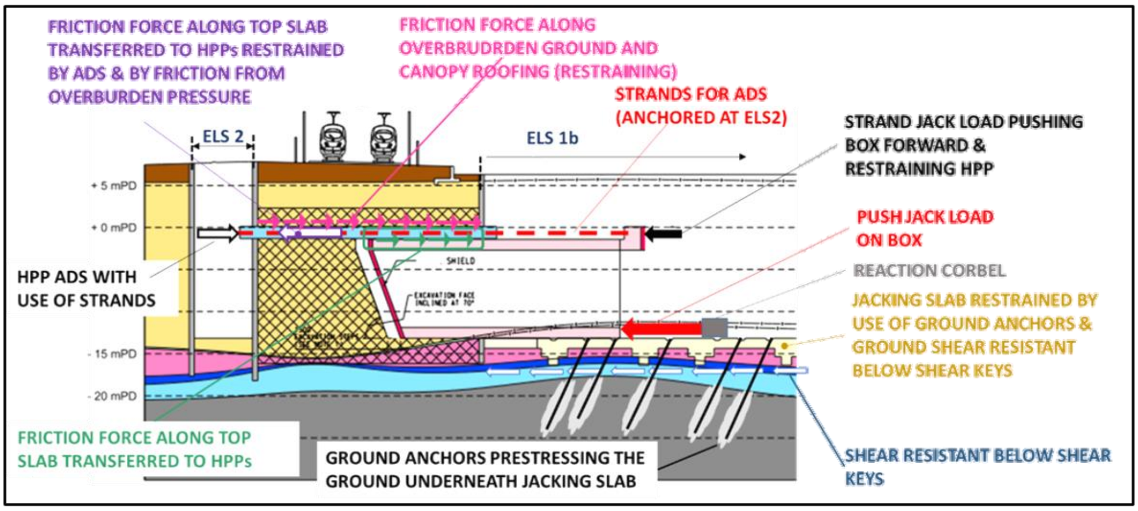

Figure 28: *Load path during box jacking*

4.5 Anti-Drag System

The restrained HPP provided the controlled sliding surface for the crown of the reinforced concrete tunnel boxes by acting as an Anti-Drag System (ADS). Thus, preventing horizontal ground disturbances to the AEL embankment during the jacking works. The HPP were restrained by an innovative strand jacking system (Figure 29). Prestressing strand bundles ran through ducts cast into ten selected pipes and were anchored at the front receiving shaft end on waler beams bearing against the HPP and vertical pipe pile wall of the receiving shaft. At the back the strands were connected to strand jacks bearing against an upstand beam at the rear of the APM and BHS tunnel boxes. The HPP and restraint system were instrumented and monitored for load and movement. The forces in the strand jacks were linked with those of the main ram jacks allowing adjustments to be made to the strand jacks depending on the roof / canopy friction forces they experienced. The upper strand jacks used were VSL's proprietary model SLU800 with a safe working load of 8,000kN. 6 No. of strand jacks were used for APM and 4 No. for the BHS respectively.

In summary uniquely the strand jack loads which were used to move the boxes forward, were are also used to prevent the HPP from moving. Thus enabling an observational approach to be adopted where the HPP movements were monitored to ensure they were minimal. Box friction forces on the bottom of the HPP being balanced against the applied strand loads.

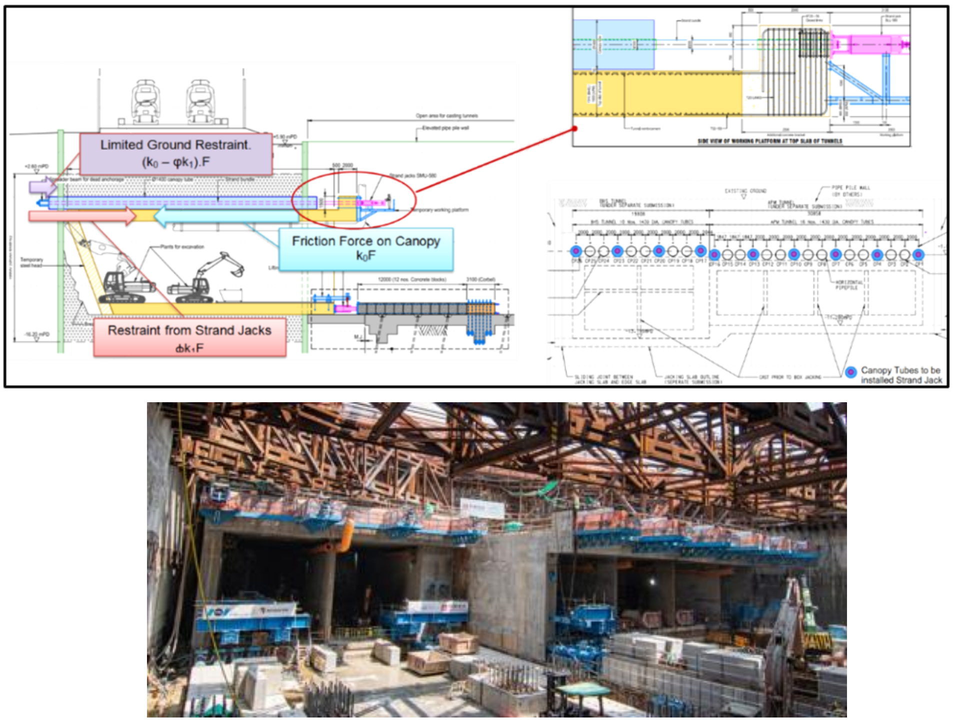

Figure 29: *Anti Drag System with strand jacking restraint*

Figure 30: *Detail Chair Shims welded to HPP (left); view 1st chair on HPP; shot-creting of gap between HPPs.*

5 Tunnel Excavation And Stabilisation Works

5.1 Tunnel Excavation

An open excavation face was adopted for the boxes after taking into consideration the improved ground conditions expected after completion of ground improvement and the dewatering, i.e. a face shield was

Proceedings DOI: 10.21467/proceedings.159
ISBN: 978-81-965621-6-8

Series: AIJR Proceedings
ISSN: 2582-3922

not necessary. The excavation was retained at 70 degrees to the horizontal and advanced in 1.5m increments ahead of the leading face of the tunnel boxes, which were cast to the same angle. The sloping face of the boxes were constructed of reinforced concrete including embedded couplers to allow for the subsequent stitching to the adjacent RC cut & cover sections. Steel plates with shear studs were cast into the nose to protect the couplers, concrete face and edges during tunnel excavation and box jacking. The horizontal roof face in front of both tunnels exposed during excavation was protected from collapsing and from excessive deformations by the canopy roofing provided by the HPP (Figure 30). Following each excavation step, chair shims were welded to the HPP at 1.5m centres to compensate for the construction tolerances during the HPP installation. The chair shims bore against cast-in steel plate strips of the tunnel box roof slabs with a maximum gap of 5mm. The HPP spanned the gap between the front of the box and the ground mass and provided a skidding interface against the tunnel boxes.

Excavation was carried out by hydraulic excavator and breaker, followed by mucking out, scaling and jacking (Figure 31). The excavation and tunnel box jacking started first with the deeper BHS box so as to maintain a minimum distance of 5m to the APM box to prevent undercutting it at the interface. A typical excavation and jacking cycle of 1.5m length was carried out in 4 days (8 shifts).

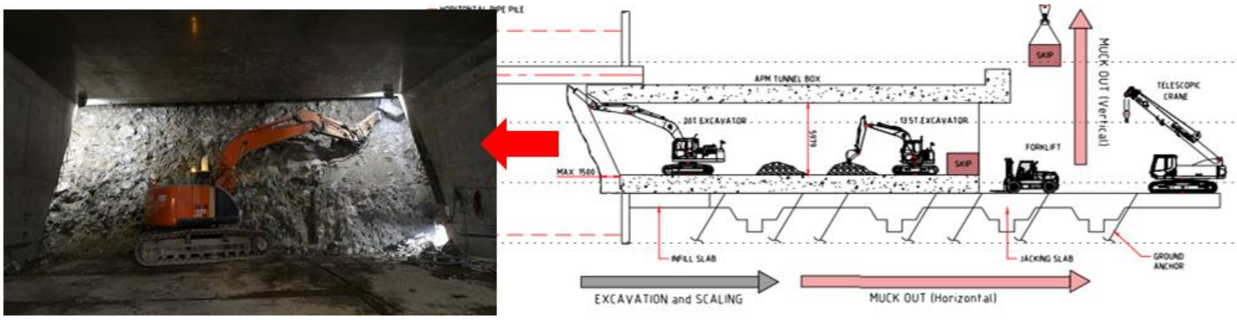

Figure 31: *Excavation with the use of hydraulic excavator and breaker*.

6 Impact Assessment On Ael

All movements of the AEL were monitored with the use of ADMS, measuring deformations of the rail tracks in three dimensions. Figure 32 presents the ADMS instrumentation above the APM box (the arrangement for BHS box was similar).

AEL rail movement monitoring during the box jacking works of the APM was provided using ADMS measuring stations ref. 58850-, 558860- and 558870- UN, US, DN, DS, 58830 UN, US, DN, DS. Overhead Line (OHL) footings were measured using stations ref. 58840- and 58860- DA & DB.

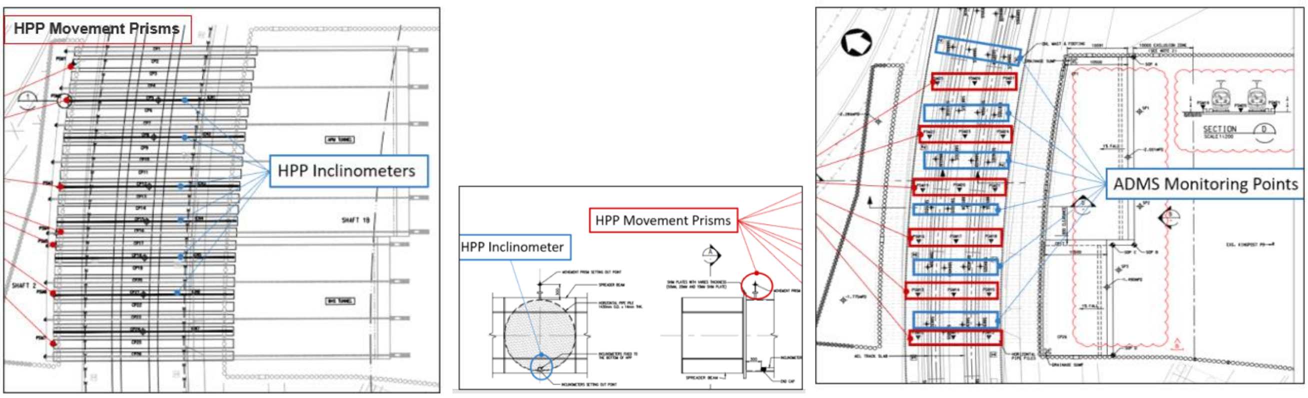

Figure 32: *ADMS arrangement of AEL below APM*

Table 4 presents the AEL settlements based on the ADMS readings from the instruments. The actual settlements of Table 4 were taken in February 2022 after the completion of the APM box jacking, i.e. the completion of the box jacking works overall. As can be seen from the readings, the maximum settlement of the AEL track was 11mm which was within the design settlement of 16mm. The accurate design and the good care provided during the execution of the works resulted in uninterrupted operation of the AEL during box jacking.

Table 4: *AEL movements at completion of the APM box Jacking*

	ADMS Monitoring Points Reference											
	58850U		58860U		58870U		58850D		58860D		58870D	
	UN	US	UN	US	UN	US	DN	DS	DN	DS	DN	DS
Induced Settlement (mm)	-4.3	-8.2	-1.2	-3.6	-6.1	-6.2	-10.8	-9.7	-10.4	-5.8	-10.8	-8.5
Maximum Settlement (mm)	-8.2						-10.8					
Design Settlement at 100% progress (mm)	-16						-16					

7 Conclusion

The APM and BHS Tunnel section of the HKIA under the AEL was the second project in Hong Kong, after the Scenic Hill tunnels, using the jacked box tunneling technique.

The project was executed by the partnership of China State and Intrafor under the care of the Airport Authority. AECOM was the designer of the box jacking works in all temporary conditions. The works included a high quality ground improvement scheme to stabilize and improve the ground properties, and the installation of a canopy roof made of HPP. The HPP, installed using micro TBM's/pipe jacking, were instrumental to ensure that the box jacking works of the two tunnels were carried out safely, without any disruption to the operating AEL railway. The APM and BHS tunnel boxes were jacked into the ground with a launching system comprising push jacks installed at the lower tail of the two boxes and strand jacks attached to the upper rear of the boxes. The push jacking forces reacted on a system of corbels constructed on the jacking slab, which was itself restrained by high capacity ground anchors anchored in rock. An innovative Anti-Drag System was installed as a canopy to the excavation roof that prevented adverse horizontal ground movements below the AEL during jacking. At the same time the ADS also served as part of the jacking system which improved the efficiency of the system and enable an 'observational' approach to canopy movement versus strand load provision. A detailed ADMS was installed to monitor the movements of the AEL tracks during the execution of the works that could give an immediate warning on adverse movement beyond the acceptable levels.

The jacking works for the APM tunnel and BHS tunnel were successfully completed within tolerances in June 2022, with the AEL movements being kept within the design expectations. The works were ultimately performed with a high level of safety, without any effect on the regular operations of the AEL. This demonstrating that the box jacking technique in Hong Kong is an appropriate construction method for tunnel construction in a settlement sensitive environment.

8 Declarations

8.1 Acknowledgements

The authors wish to acknowledge the valuable contribution of the large project team (designers, site team and supervision) that led to a successful project.

8.2 Publisher's Note

AIJR remains neutral with regard to jurisdictional claims in institutional affiliations.

How to Cite

Tsaparas *et al.* (2023). A Technical Overview of Contract No. 3801 APM and BHS Tunnels on Existing Airport Island: Jacked Box Tunnels under AEL. *AIJR Proceedings*, 147-165. https://doi.org/10.21467/proceedings.159.13

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