Geotechnical Design and Performance of a Jacked-in-Place Subway in the First Application of the Rectangular Tunnel Boring Machine Technology in Hong Kong

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Abstract

The construction of a 140 m long subway at the Kai Tak Development was faced with aggravated constraints of urban settings –including congested utilities, lack of space, traffic concerns, proximity to structural foundations and existing facilities, etc. Combined use of the rectangular tunnel boring machine (RTBM) technology and segmental jacking techniques provided an innovative solution. This paper gives an overview of the design and construction process, the geotechnical challenges encountered and the measures to tackle them. Specifically, earth pressure balance (EPB) underlying the technology and jacking force assessment will be discussed. The successful completion of this project demonstrated the feasibility of the RTBM technology in typical geological conditions of Hong Kong, and the potential for routine applications for tunnel-type underground facilities particularly in congested urban areas.

Keywords: Rectangular TBM, Tunnel, Hong Kong

1 Introduction

With the airport at Kai Tak relocated to Chek Lap Kok in July 1998, the vacated site constituted a good opportunity for a major re-development in the heart of Hong Kong. The resulting Kai Tak Development (KTD), more than 320 hectares in size, is being transformed into a vibrant new community. As part of the infrastructure of the KTD, a pedestrian subway SW4 is constructed to provide connectivity with the Choi Hung area.

Subway SW4 is of internal dimensions 4 m wide by 3 m high. About 140 m in length, it passes underneath several major roads as indicated in Plate 1. In particular, it has to be routed through closely-packed piled foundations of the Kwun Tong Bypass viaducts, with clearances as small as 2.7 m. Vertically, it is constrained by a number of major utilities, including in particular several water-bearing culverts and conduits on top.

A trenchless tunnelling method using, for the first time in Hong Kong, a rectangular tunnel boring machine (RTBM) was adopted for the construction. This paper focuses on the geotechnical aspects of the works. Challenges encountered during design and construction are also discussed.

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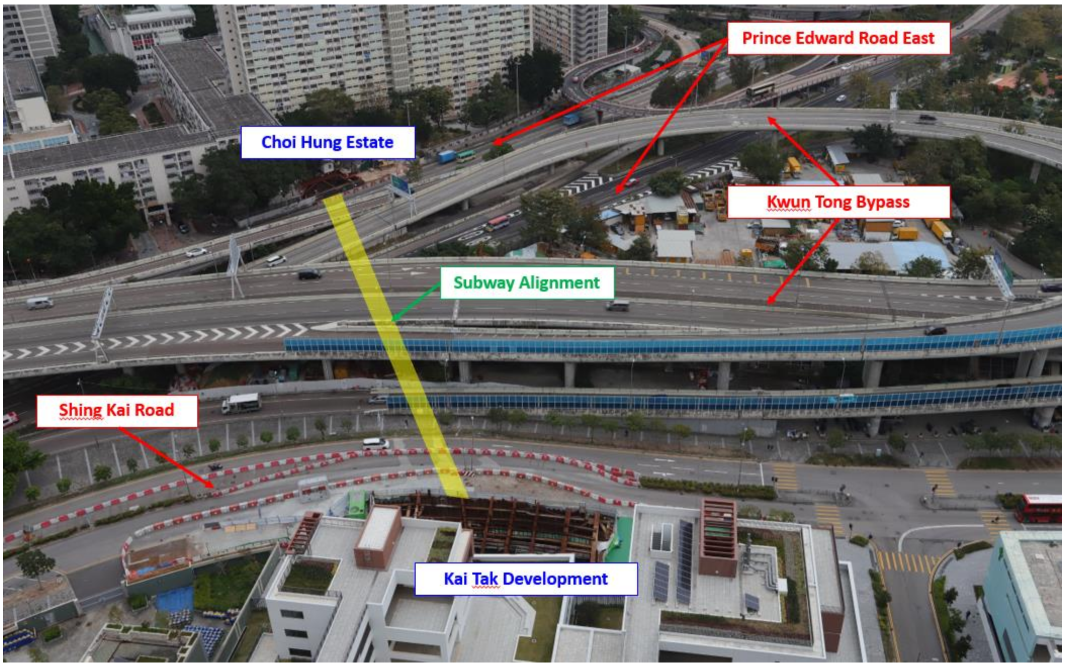

Plate 1: Subway SW4

Figure 1: General View of RTBM

2 Geotechnical Design

2.1 Geology and Soil Properties

For evaluating the viability of the technology, additional ground investigation was conducted, comprising drillholes PS-1, PS-3 and PS-4 and inclinometers I3, I4, I5 and I6, as shown in Figure 2. The geological conditions revealed matched the previous ground investigation from drillholes DH15, DH16 to DH18 and 11521-PE-16 and 17. Generally, the site comprises fill, alluvium and completely decomposed granite (CDG), with average thicknesses of 6 m, 14 m and 33 m respectively. The tunnel alignment is located partly in fill and mostly alluvium. The ground condition was complex owing to the presence of many boulders, especially the location closely underneath the 4-cell box culvert where gravel or cobble fill material was found.

2.2 Potential Underground Obstructions

The presence of large underground obstructions would directly affect the viability of RTBM tunneling. Borehole investigation information alone might not be adequate as it only gave discrete geological information at certain locations. While machine was designed to cope with gravel fill material with cobbles size up to 150 mm in diameter, the potential presence of larger sized boulders, left-in structures etc, was a concern. A geophysical survey along the proposed tunnel alignment was therefore conducted, adopting the multichannel analysis of surface waves (MASW) method, which assessed the elastic condition, or stiffness, of the ground. By interpreting the velocities of surface waves, the shear wave velocity (*Vs*) below the surveyed area was derived, which could be related to stiffness of the ground. The result from the geophysical survey was verified by the borehole logs to determine the soil stratum distribution along the tunnel alignment. The survey revealed no major underground obstructions.

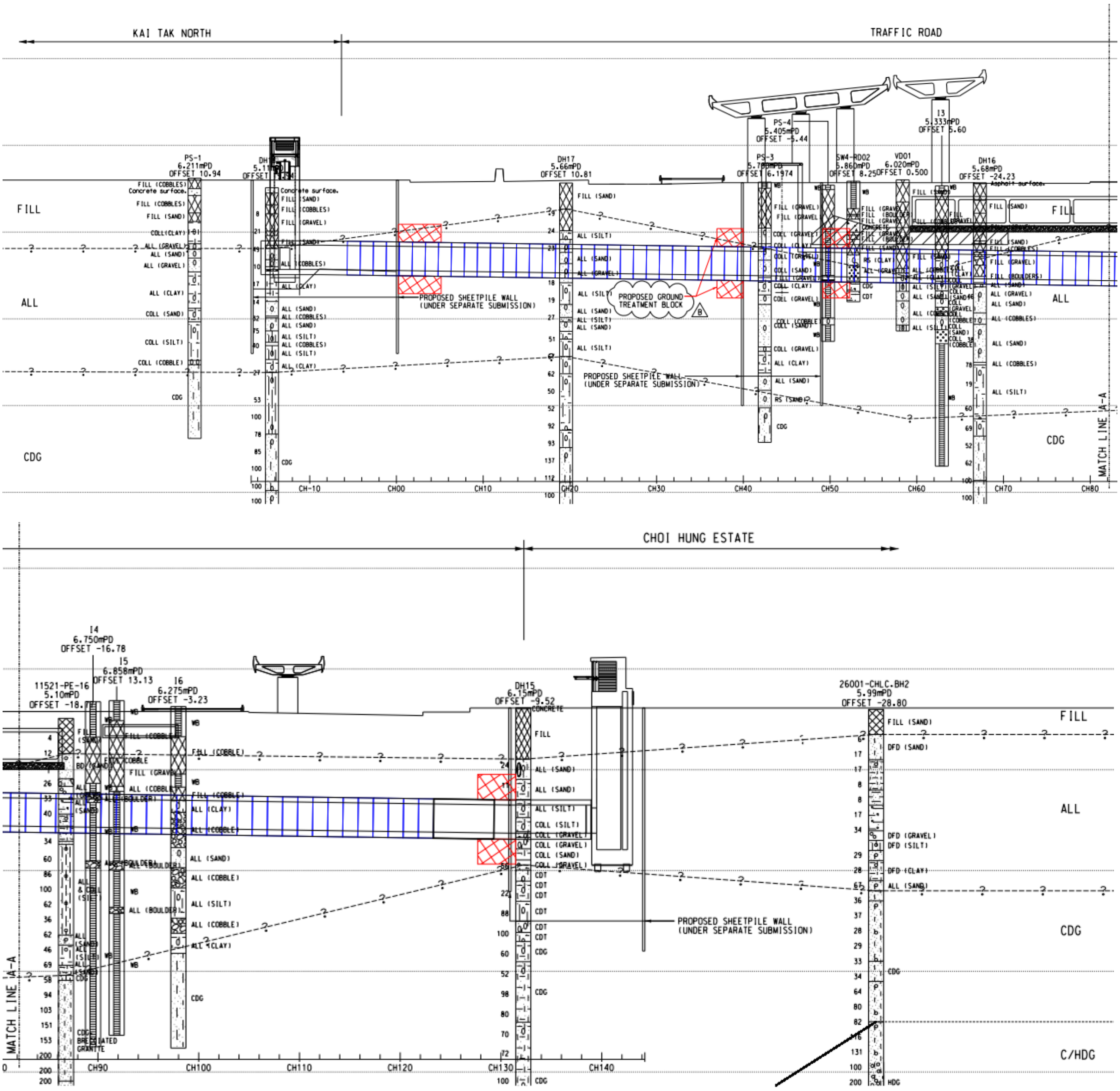

Figure 2: Geological profile interpreted from boreholes

2.3 Soil Properties and Soil Conditioning

Soil strength parameters were determined from consolidated undrained triaxial tests with pore water pressure measurement. Stiffness parameters were deduced from empirical correlation with SPT-*N* values.

Table 1. Design parameters for soils

Soil type	Bulk Unit Weight (kN/m^3)	Cohesion, c' (kPa)	Friction Angle, ϕ' (degree)	Elastic Modulus, E' (kPa)
Fill	19	0	33	9000
Alluvium	19	4	33	20400
CDG	19	4	33	39895

Geological profile and soil parameters were important information for the mechanical design of the RTBM including the cutterhead and cutting tools, as well as the tunnelling operation. The choice of soil conditioners and details of conditioning were determined based on the soil parameters and assessed by on-site tests. The soil in front of the cutterhead was mixed with bentonite, water and additives to form a slurry material for RTBM excavation followed by disposal through a screw conveyer. Soil conditioning assisted in establishing a positive balance pressure and hence reduced water permeability. The conditioned soil had better flowability, plasticity and consistency. This would consequently contribute to more smooth execution and productivity of the tunnelling works.

Figure 3: Soil before and after conditioning

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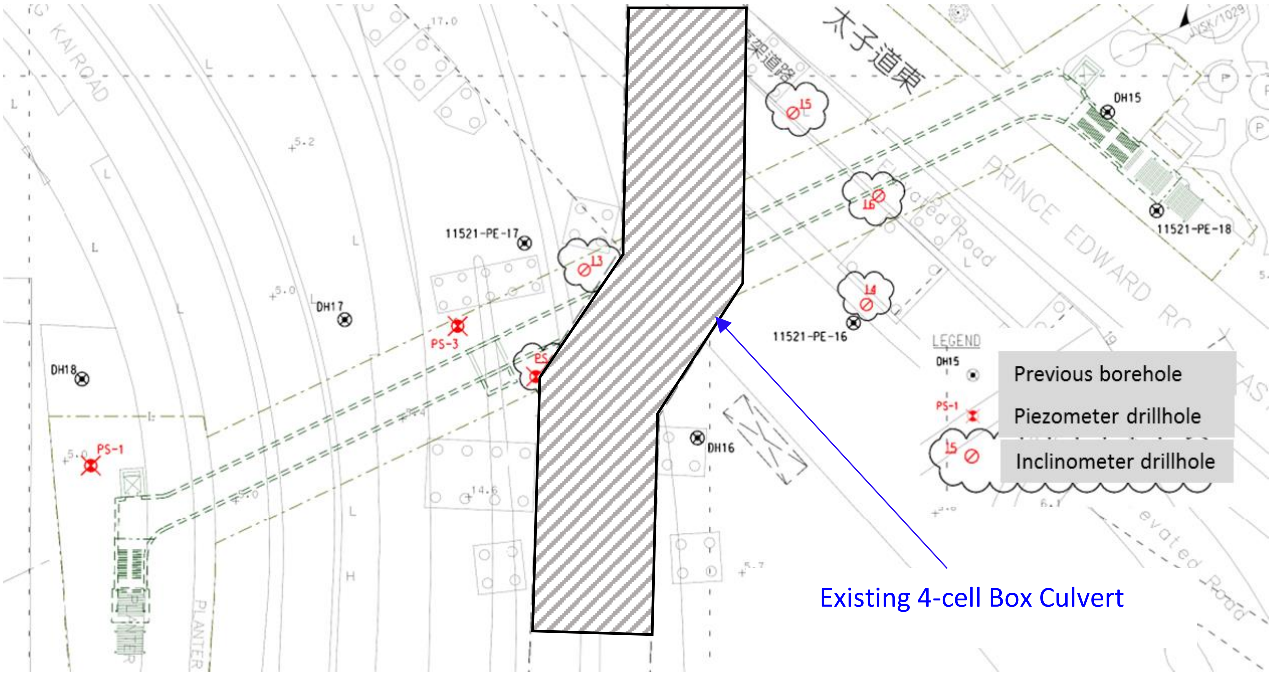


Figure 4: Locations of ground investigation boreholes

2.4 Hydrology

Groundwater monitoring has been carried out on site since June 2017, covering both wet and dry seasons. As shown in Figure 5, the highest measured groundwater level was +3.2 mPD. A design groundwater level at +3.5 mPD was adopted. It is noted this high groundwater table can pose severe risks for traditional mined tunnel construction methods involving manual underground excavation or in-situ structural construction.

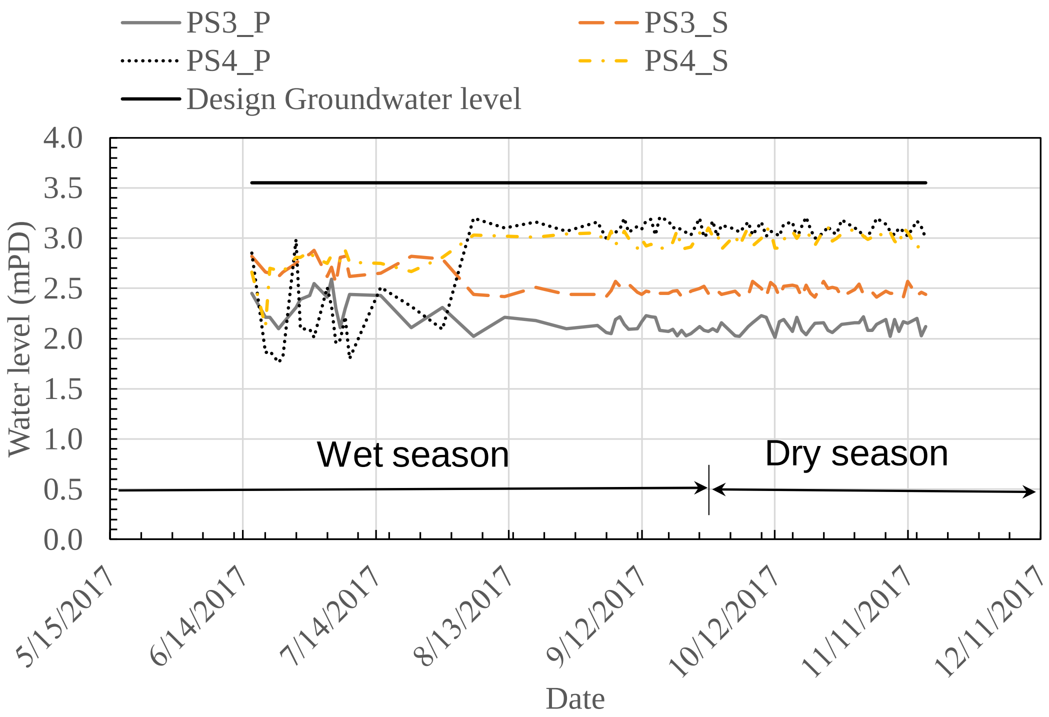


Figure 5: Groundwater monitoring records during design stage

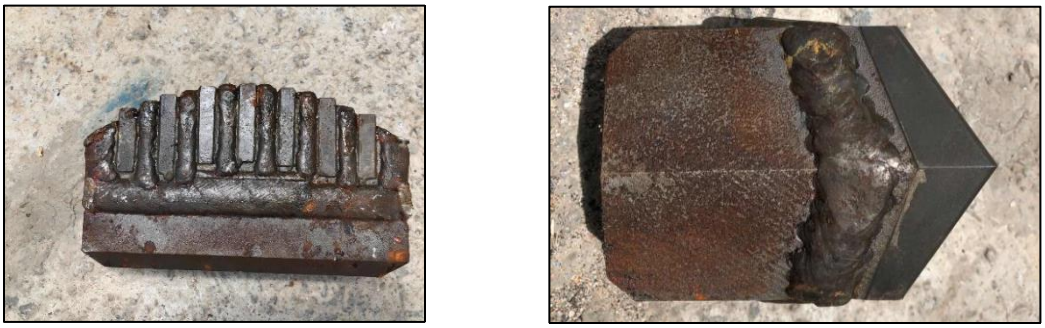
3 Design of the Rtbm

3.1 Cutterhead and Cutting Tools

For soft soil ground conditions, a full-face cutting profile is preferable as this reduces over-excavation and squeezing of the soil, and therefore the impact to underground. It will also help control the face pressure more smoothly, and both short-term and long-term settlement will be mitigated. To this end, the cutterhead design should be aimed at minimizing blind spots not covered by the cutting tools as far as possible.

In the case of Subway SW4, a large central cutting tool was adopted to cover the majority of the rectangular tunnel cross section. The rest of the area within the cutting profile is catered for by four eccentric cutting tools. The cutting profile of small cutting tools follow a rectangular path in order to reduce blind area. The overall coverage of this configuration is 92% of the face area, which is considered sufficient for the project.

Another important design aspect is ensuring that the cutting tools are strong enough to overcome the high friction and torque during tunnelling. Selected based on the project ground condition, two categories of cutting tools were utilised, namely rippers and scrapers. Rippers are of high strength and anti-wear capacity. They are used for breaking dense soil strata or hard materials such as cobbles. Scrapers mainly serve to move the excavated soil into the RTBM excavation chamber. Their cutting tracks need to fully cover the whole cutting profile to ensure the efficiency of soil collection.



Ripper Scraper

Figure 6: Rippers and Scrappers

3.2 RTBM Face Pressure

The RTBM used in the project worked on the earth pressure balance (EPB) principle. For operation safety, it was important to establish and maintain an appropriate face support pressure. An inadequate pressure would lead to instability with excessive ground movement or even collapse of the tunnel face. On the other hand, an excessive pressure might result in ground heave.

Tunneling in urban areas required particularly stringent control of ground movements to minimize the effect on overlying and nearby buildings, structures and utilities. Reference was made to GEO Report No. 298 in determining the design target and maximum face pressures, on the basis of the soil parameters described in section 2 above.

Maintaining the face pressure at the target value during the tunnel boring required the combined actions of adjusting the thrust force applied, the cutterhead rotation speed and direction, the excavated soil discharge rate and the injection of soil conditioners. It was a dynamic process and varied with geological conditions and site conditions being encountered. Making reference to past projects

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and the site specific geological characteristics, the project team established a set of control parameters for the RTBM operation.

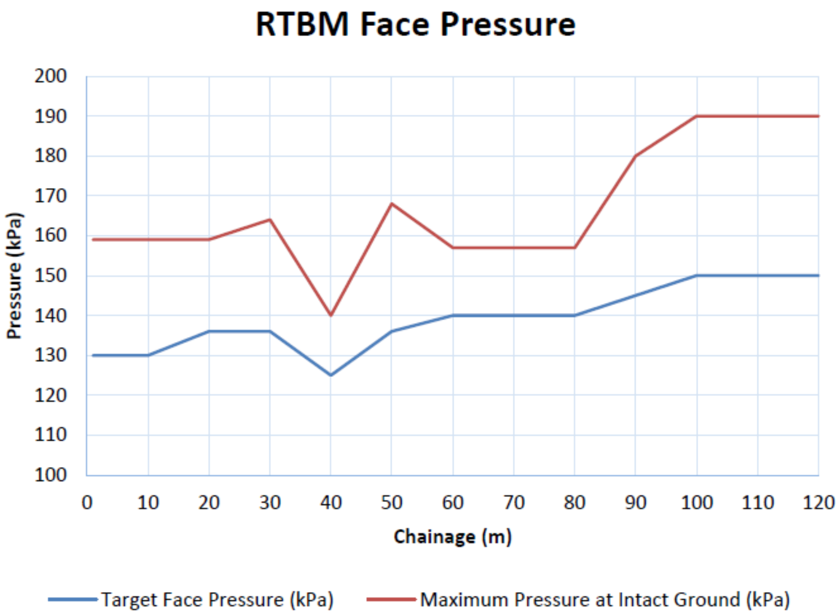

Figure 7: Target operation face pressure

3.3 Ground Improvement for RTBM Break-In and Break-Out

Along the RTBM tunnel alignment there were three shafts – a launching shaft, an intermediate ventilation shaft, and a receiving shaft. At the RTBM break-in and break-out locations, vertical openings had to be made in the shafts. To ensure ground stability, ground improvement works were designed and undertaken. Stability analyses using the SLOPE/W software was carried out for designing the grouting extent and grout strength. The design grout uniaxial compressive strength (UCS) strength adopted for this project was 1.0 MPa.

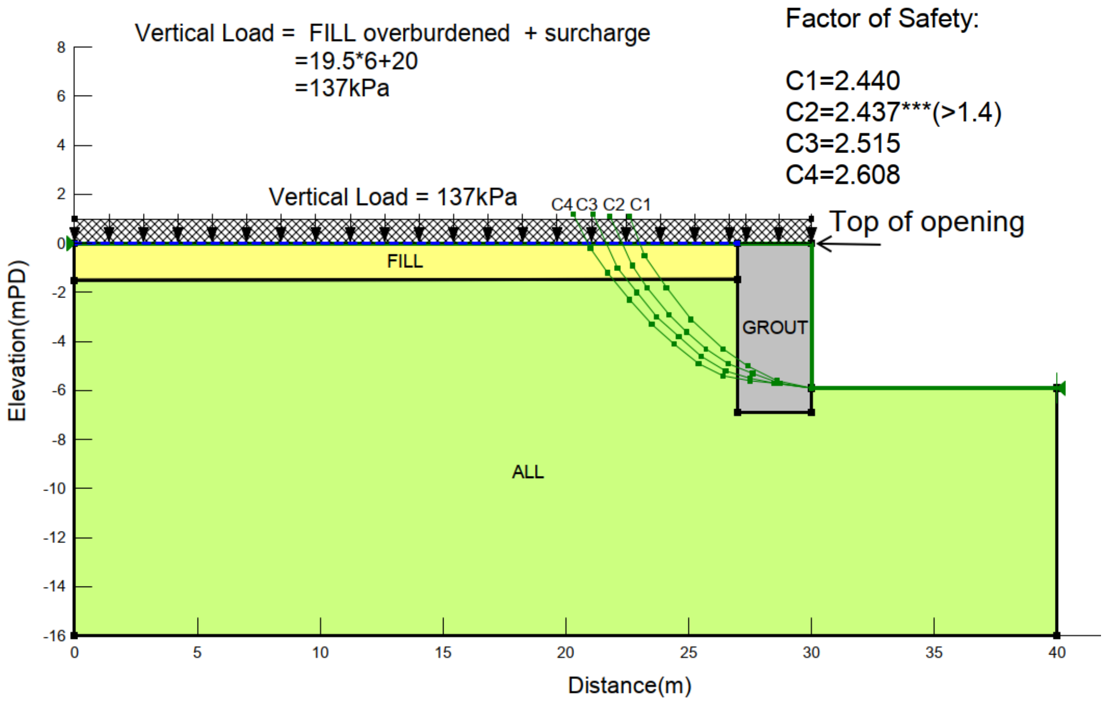

Figure 8: Ground improvement design for RTBM break-in and break-out

3.4 Jacking Force Estimation

Jacking force was applied to balance two types of resistance. The first was the frictional force between the jacked-in-place segments and the surrounding soil. The second was the reaction between the RTBM cutterhead and the soil in front of it. An accurate estimation of the jacking force was a challenging task. A variety of methods have been put forward for estimating the jacking force internationally. Peng (2015) and Sterling (2020) provided comprehensive reviews on the subject. Many of the methods, however, are not specifically related to segment jacking using RTBM. In recent years, there were a number of segment jacking projects undertaken using RTBM in Mainland China, and several design codes and references have been published. The design of this project made reference to China Municipal Engineering Association (CMEA) (2020).

$$P = 2(B + H)Lf + B'H'Pc \quad (1)$$

where P = jacking force, B = segment width, H = segment height, L = jacking distance, f = friction force per unit area, B' = width of the RTBM cutterhead, H' = height of the RTBM cutterhead, and Pc = passive earth pressure in front of the cutterhead.

$$Pc = K_0\gamma(h + 2H/3) + \gamma_w h_w \quad (2)$$

Where K_0= earth pressure coefficient at rest ($1-\sin\phi'$), h = cover depth of the tunnel, γ = unit weight of soil, γ_w = unit weight of water, h_w = height between groundwater level and one-third of RTBM cutterhead height (calculated from invert level).

The most challenging part of the estimation was the friction force per unit area f. Extensive experience has shown that where lubricants are applied between the annulus between the segments and the soil during jacking and are functioning, the value of f is in the range of 8.0 to 11.0 kN/m^2 (CMEA (2020) – Table 4.4.3 Silty SAND). Following a review of the geological condition, (SPT-*N* value in the range of 12 to 32), a value of 10.0 kN/m^2 was adopted for the project.

4 Construction Performance

4.1 Face Pressure During RTBM Advancement

The project team maneuvered the machine by adjusting the advancement and mucking out speeds to control the real-time face pressure during excavation to match within the target face pressure. There were four pressure sensors installed in the bulk head of the machine for monitoring the actual face pressure developed during RTBM advancement.

Figure 9 presented the actual face pressure measured during tunnel excavation in relation to the design target pressure. It can be observed that the measured pressure was controlled to be fairly constant throughout the operation.

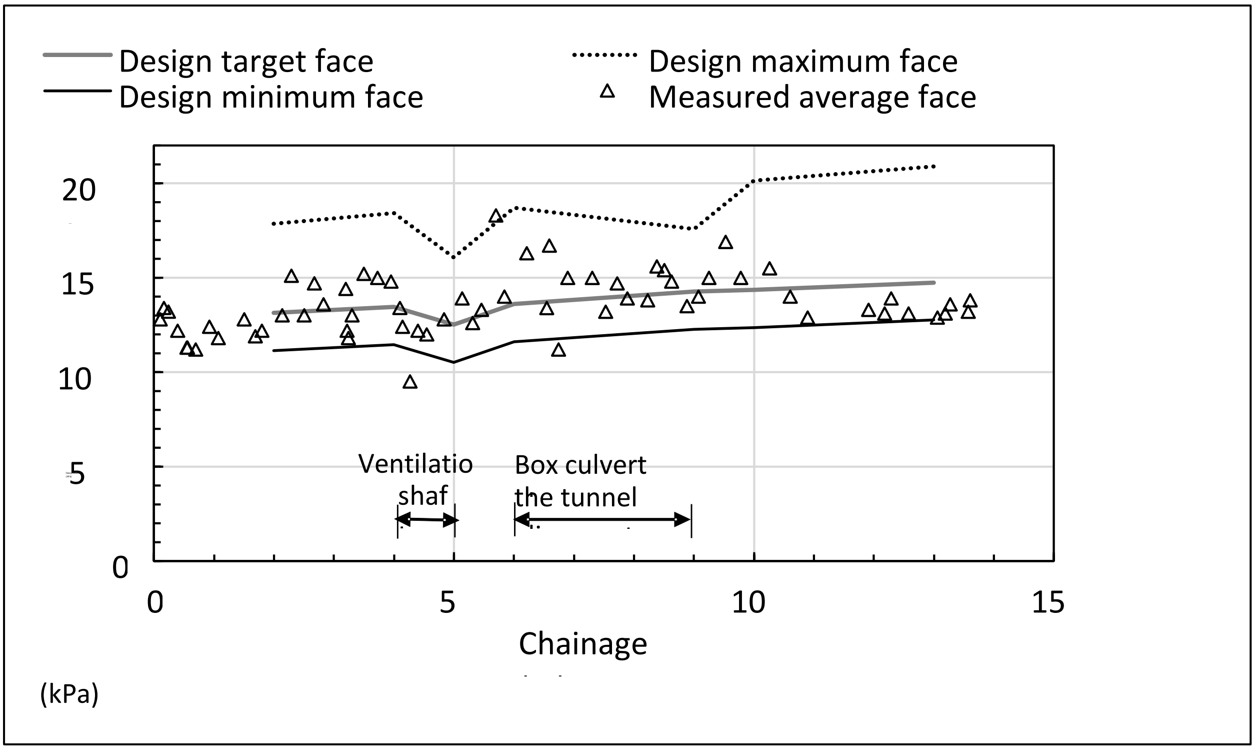

Figure 9: Comparison between design and measured face pressure

4.2 Recorded Jacking Force

Based on the jacking force estimation method, the maximum jacking force required for completion of the tunnel was 2858 tonnes at a jacking length of 130 m. A main jacking system with a capacity of 3600 tonnes was used for this project. In addition, an intermediate jacking station was incorporated in the machine as a contingency jacking capacity. A comparison between the estimated and the recorded jacking forces during RTBM advancement is shown in Figure 10. It is evident that when RTBM advanced though the grouted zones, the jacking force increased. Another observation is the increase of jacking force from Chainage 80 m to 100 m where the machine was passing underneath the 4-cell box culvert below Prince Edward Road East. Ground investigation records show that the presence of gravel or cobble fill material within this region, and higher torque and thrust force were required for the machine to pass through.

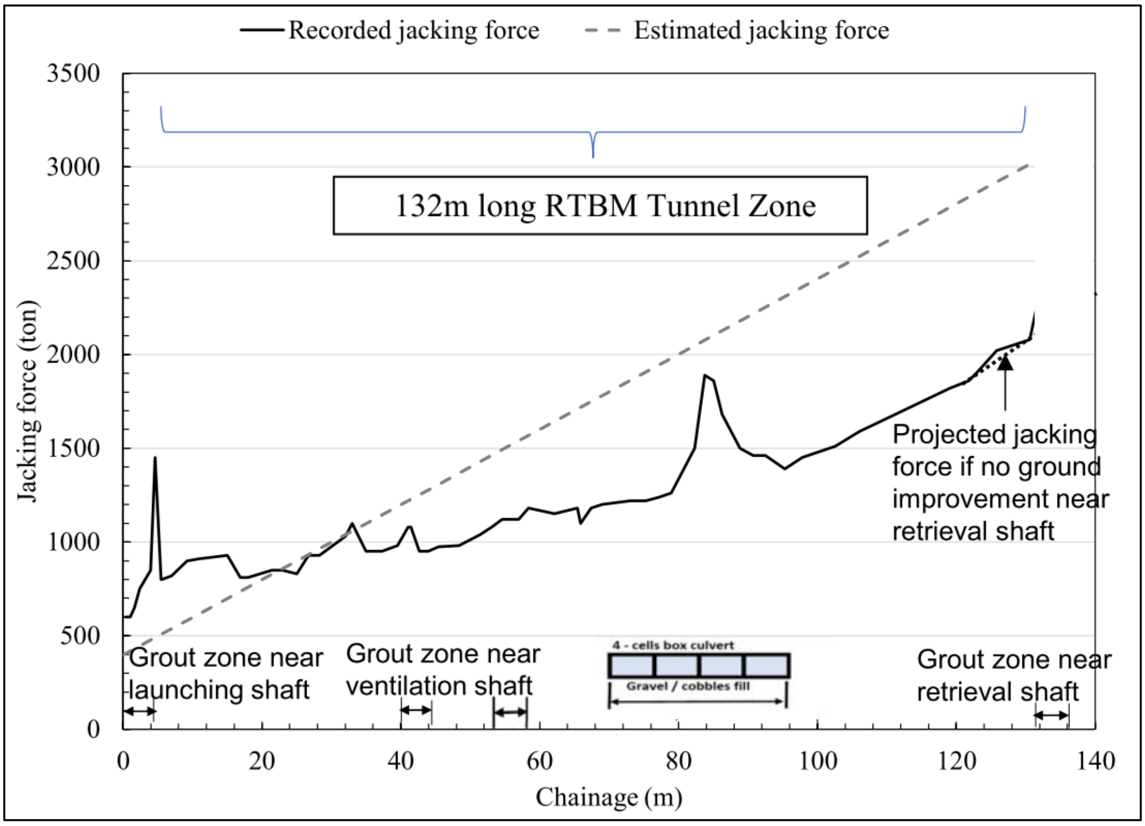

Figure 10: Comparison between estimated and recorded jacking force

Based on the measured face pressure and jacking force, the friction force per unit area *f* between the segments and soil could be back-calculated. Based on the CMEA formula in section 3.4 above, the maximum jacking force required to overcome the passive earth pressure in front of the cutterhead is 465 ton and the recorded maximum jacking force for the whole operation is approximate 2300 - 2400 ton, thus, a friction force per unit area *f* is derived to be approximately 7.5 kN/m^2 based on the formula, which corresponded to the lower bound of the design assumption.

4.3 Ground Settlement Monitoring

Ground surface settlement monitoring points were installed along the tunnel alignment. Some were installed above the tunnel center line and some at 1 m offsets, as shown in Figure 11. Assuming 1% volume loss, the predicted maximum settlement due to the tunnelling is 12mm based on the geotechnical impact assessment report. The measured settlement was well within 12mm prediction. The well-controlled settlement serves to demonstrate that the applied face pressure has been appropriate.

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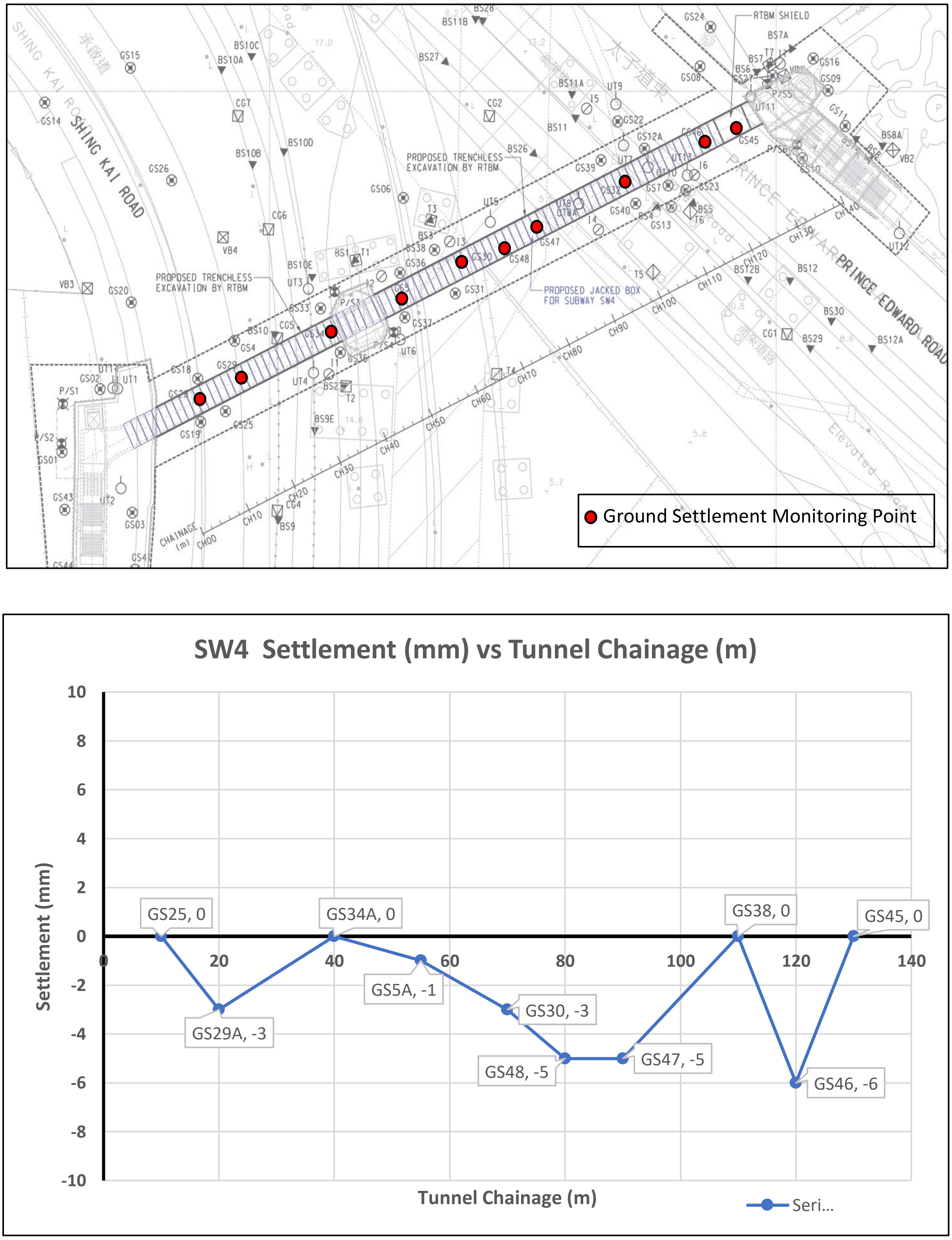

Figure 11: Measured ground surface settlement along the tunnel alignment

5 Conclusions

The project Subway SW4 saw the successful implementation of a jacked-in-place pedestrian subway using the first RTBM in Hong Kong. Albeit the technology has been commonly applied in Mainland China and Japan, the geological conditions of this project and the characteristics of Hong Kong soils presented unique challenges. Employing fully-mechanized excavation and precasting of tunnel segments, the RTBM technology has brought about a multitude of benefits, including enhanced works safety and working environment, effective management and control of construction risks, raising construction quality, and promoting sustainability.

The technology has good potential for application in delivering tunnel-type facilities particularly in congested urban areas. In the geotechnical aspect, the following conclusions can be drawn:

(a) Geophysical survey provides very important supplementary information to borehole investigation for RTBM cutterhead and screw conveyor design to minimize the risks arising from complex geological conditions.

(b) The friction force per unit area f back calculated in this project is approximately 7.5 kN/m^2. For future designs in similar geological conditions, a value of, say, 10 kN/m^2 can be considered.

(c) Face pressure estimation in accordance with GEO Report No. 298 gave satisfactory outcome in the RTBM operation.

(d) The resulting measured settlement is well within that corresponding to a 1% volume loss assumption.

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