Hong Kong West Drainage Tunnel – Review of Key Geotechnical Aspects

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ABSTRACT

Hong Kong West Drainage Tunnel (HKWDT) will intercept stormwater drainage between Tai Hang and Cyberport, effectively safeguarding the most densely populated areas of northern Hong Kong (HK) Island from the risk of flooding. In January 2011, two large diameter hard rock tunnel boring machines (TBM) completed breakthrough of the 10.7 km main tunnel, which is the longest drainage tunnel in HK. The whole drainage scheme comprises over 21 km of interconnected tunnels, adits and dropshafts, which have provided a wealth of information on structural geology, fault locations, ground and groundwater conditions. Eight major faults, numerous subsidiary faults, shear zones and contact zones were encountered. The geological structure encountered and particularly the groundwater conditions were the major factors controlling the progress of the TBM's. Major grouting works were required in the west of the HKWDT in the Telegraph Bay Fault and most notably in the Sandy Bay Fault where ground conditions were extremely poor. All information collected and practices adopted will be provided to the tunnel database maintained by the Geotechnical Engineering Office (GEO). The data provided will make a major contribution to existing knowledge on ground conditions and tunneling in HK.

1. PROJECT HISTORY

Rapid urbanization, change in land use and a substantial increase in the paved area of HK have resulted in a significant increase in surface run-off, affecting much of the lower catchment area of Northern HK Island. Despite local improvements to the 50 years old drainage system, flooding remains a problem in the summer months. During heavy rainstorms, high quantities of storm water run-off can flow from the steep upper hillside catchment down into the lower urban areas, causing flooding, traffic disruption damage to property and in extreme cases potential risk to life.

In response to this and to meet the community's increased expectations for higher flood protection standards, the Drainage Services Department (DSD) commissioned a drainage master plan study for Northern HK Island to assess the existing drainage systems in the area. The drainage master plan study recommended three key components to be implemented, one of which is HKWDT.

2. PROJECT DETAILS

Ove Arup and Partners HK Ltd (Arup) were commissioned by DSD in March 2006 to undertake the design, tender and construction supervision of the HKWDT. The whole system is designed to discharge a peak flow of 135 m^3/s to the outfall at Cyberport equivalent to a 200-year storm event. The construction contract was awarded to the Dragages–Nishimatsu Joint Venture in November 2007 and is now nearing completion in 2012.

The main tunnel is the longest drainage tunnel in HK running from Tai Hang in the east to Cyberport in the west with a distance of 10.7 km. The main tunnel was excavated by two hard rock double-shield TBM with excavation diameters of 7.2 m for the eastern TBM tunnel and 8.2 m for the western TBM tunnel. The main tunnel branches into over 8km of approximate 3m diameter horseshoe shaped horizontal adits, which were excavated by drill-and-blast method. Adits connect to vertical dropshafts up to 170 m deep, that were excavated by a variety of methods, the most common being raise boring (23 nos.), other shafts being constructed by hand dug caisson, mechanical excavation and reverse circulation drilling. This is the first project in HK to systematically rely on the use of raise boring for vertical shaft excavation, a major and potentially problematic component of the project. At the top of the dropshafts, intake structures intercept the existing stream courses and culverts. The intake sites are scattered throughout the urban fringe including the Mid-Levels Scheduled Area (MLSA). Each intake is a mini construction site with deep excavation and lateral support (ELS) works generally formed by pipe pile cofferdams. Stability and surface settlement have been of paramount concerns necessitating much instrumentation which has been collated into a Tunnel Data Management System for close monitoring by the site supervision team.

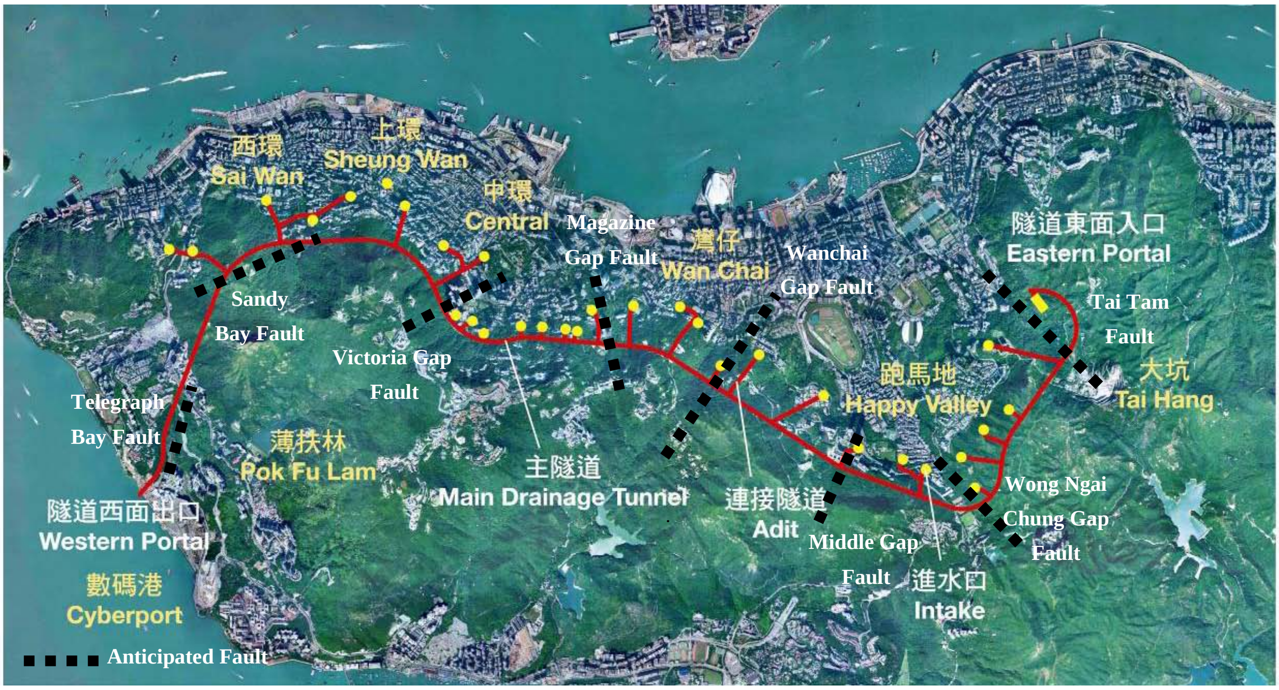

Figure 1: Overall scheme of HKWDT

3. DESIGN CRITERIA & PROCESS CONTROL

HKWDT is designed mainly as a drained tunnel dependent on pre-excavation grouting to reduce water inflow during construction to a set of acceptable limits defined in the construction contract:

(a) 0.2 litre/minute (L/min) per metre of probe hole ahead of the excavation face and not more than 1 L/min from any 5m length of probe hole;
(b) 10 L/min over any 100m length of excavated tunnel, adit or dropshaft;
(c) 2 L/min through any excavation face; and
(d) 300 L/min at any portal.

Probing was carried out typically up to 30 m ahead of the TBM and water inflow was measured from the probes. If criteria (a) was exceeded then pre-excavation grouting was carried out by intruding micro-fine cement into the rock mass through the probe holes which passed through circular openings in the front of the rear shield. After completion of grouting, an additional probe hole was carried out to verify the performance of the grouting works. Further grouting would be performed if necessary. For zones of high groundwater inflow such as the Sandy Bay Fault up to 2 % micro-silica was added to the micro-fine cement to ensure better penetration of the rock mass. It was fundamental that during the grouting operation skilled operatives closely monitored the actual site situation and reviewed the performance of the grouting works to select the most suitable grout materials, mixes and pressures compatible with the observed ground conditions.

4. KEY GEOTECHNICAL ASPECTS

With over 21 km of interconnected tunnels, adits and dropshafts, the project has provided a wealth of information on ground and groundwater conditions, fault locations and characteristics which will be extremely useful information for other underground projects in HK. The majority of current observations below are based on the TBM tunnels, with data from the adits and dropshafts still under review. When complete all data will be provided to the tunnel database maintained by the GEO for record and technical development, including the continuing update of geological maps by the Hong Kong Geological Survey of GEO. GEO have been heavily involved throughout the project providing useful comments on the construction contract and commenting on design submissions particularly those relating to the MLSA where seven Intakes and associated adits and dropshafts are located.

4.1 Regional Geology

Based on the published geological data (Sewell et al., 2000a) and limited ground investigation information it was anticipated that the fine to medium grained granites of Cretaceous age would predominate in the eastern part of the tunnel drive and also be found more locally near the Western Portal. Volcanic rocks, of similar age (Sewell et al., 2000b) were anticipated in the central parts of the scheme between Pok Fu Lam and Mount Cameron.

The pre-construction ground models were proved to be quite accurate particularly in the case of the granites. Some changes in lithology were noted underlying Jardines Lookout, where the change from fine to medium grained granites, was displaced 500m further west than anticipated and similar changes and more minor differences west of Victoria Gap where the fine grained granites were absent completely, instead replaced by medium grained granites.

For the volcanic rocks there were significant differences on the western side of the project where the change from fine grained granites to fine ash vitric tuff was originally expected between Pok Fu Lam and High West. In reality the geological boundary and highly fractured contact zone was some 550 m to the east running up to the subsidiary geological structure associated with the Sandy Bay Fault.

Before construction, it was anticipated that there would be large differences in the unconfined compressive strength (UCS) of the rocks encountered. Based on the ground investigation and laboratory testing, average values for the granites were approximately 156 MPa and for the volcanics 205 MPa, although it had been found that for some samples of fine ash vitric tuff a maximum value of 339 MPa was obtained in the vicinity of Victoria Gap. These typical values were confirmed on site when the contractor undertook additional testing and confirmed a maximum UCS value of 353 MPa. The western TBM was slowed down to penetration rates of less than 0.2 m/hour and TBM cutter discs and the integral bearing units experienced very significant wear and had to be changed on a daily basis. Unfortunately the extremely strong vitric tuff had coincided with a rock mass that had very few joints making it difficult for the cutters to ‘pluck’ the rock from the face, instead progress could only be made by a slow grinding operation.

4.2 Structural Geology & Faults

Based on published geological data and pre-contract ground investigation, eight major faults (Figure 1 & Table 1) and approximately twenty two subsidiary faults and photolineaments were identified, intersecting the alignment of the main tunnel. The three major faults identified in the granites of the eastern TBM drive were the Tai Tam Fault, Wong Nai Chung Gap Fault and Middle Gap Fault. All three faults were characterized by local shearing, minor fault breccia and occasional fault gauge over quite limited extents. Maximum groundwater inflow in the eastern faults was less than 2 L/min/m measured in probe holes and more typically

1 L/min/m and was therefore easily managed. Maximum grouting volume per 30m round of probes was 40 m^3 in the Tai Tam Fault and less than 20 m^3 in the Wong Nai Chung and Middle Gap Faults. The Wong Nai Chung Gap Fault was found to have major influence immediately to the east of the anticipated location as it was found in a dropshaft adjacent to the French International School on Blue Pool Road.

Table 1: List of faults anticipated in pre-construction stage

Fault	Anticipated chainage (m)	Actual chainage encountered (m)	Observed ground condition	Q Value	Infiltration rate in probing (L/min/m)
Tai Tam Fault	Ch 645	Ch 635 - Ch 655	Highly fractured rock mass	0.1 - 1	1.5 - 2
Wong Nai Chung Gap Fault	Ch 2130	Ch 2095 - Ch 2135	Highly fractured rock mass	0.1 - 10	0 - 0.2
Middle Gap Fault	Ch 3270	Not obviously identified	No adverse ground conditions observed.	-	0 - 0.2
Wanchai Gap Fault	Ch 4540	Ch 4050 - Ch 4500	Intermittent fractured rock mass	1 - 4	0 - 0.2
Magazine Gap Fault	Ch 5080	Ch 4800 - Ch 5270	Intermittent fractured rock mass	1 - 4	0.5 - 2
Victoria Gap Fault	Ch 6570	Ch 6510 - Ch 6535	Highly fractured rock mass	0.1 - 1	0.5 - 1
Sandy Bay Fault	Ch 8360	Ch 8305 - Ch 8335	Highly fractured rock mass	0.1 - 1	0 - 0.5
Sandy Bay Fault (Subsidiary)	Ch 8960	Ch 8985 - Ch 9065	Severely fractured rock mass	0.03 - 1	0.2 - 1.5
Telegraph Bay Fault	Ch 10160	Ch 9455 - Ch 9950	Severely to highly fractured rock mass	0.03 - 1	0 - 3.5

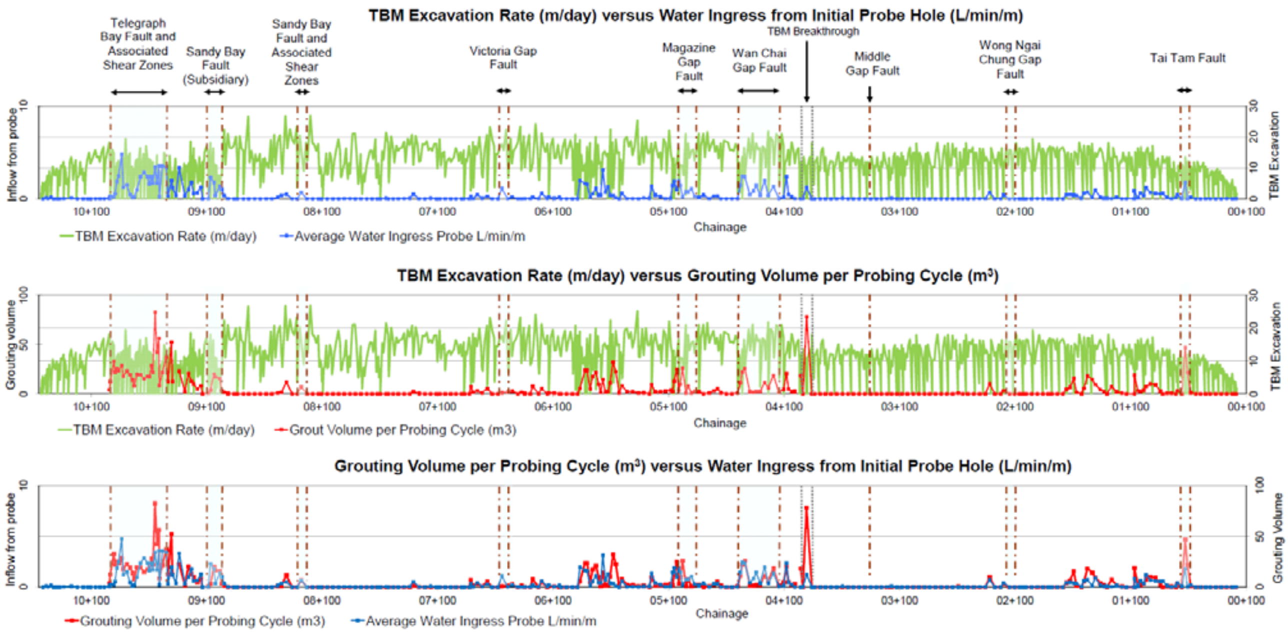

Figure 2: Summary of water inflow, grout quantities & TBM excavation rate

The western TBM experienced little difficulty with the Wanchai Gap Fault, Magazine Gap Fault and Victoria Gap Fault where groundwater inflows measured in probe holes were less than 2 L/min/m and grout volumes less than 30 m^3. 600 m to the west of the Magazine Gap Fault, further faulted ground was encountered with similar water inflows and grout takes as the main fault.

The Sandy Bay Fault and Telegraph Bay Fault at the western end of the project were identified at the project planning stage as significant risks to progress of the western TBM. A major concern was that the tunnel alignment ran parallel or sub-parallel with both faults which is a well documented high risk situation (Barton N., 2006), which has led to TBM on other projects having become stuck and even abandoned. Parallel fault zones tend to destroy much of the tangential stress necessary to ensure stability of the arch and crown of the tunnel. In addition, it was known that both the extent and severity of the ground and groundwater conditions could be quite extreme. Options for tunnel re-alignment of the tunnel near the Telegraph Bay Fault were quite limited owing to the fixed location of the outfall at nearby Cyberport, however, re-alignment was possible near the Sandy Bay Fault. Under the original alignment it was possible that the alignment which is in a 600 m radius curve at this location could even pass through the fault twice. After further ground investigation in 2006 and review of the most likely incidence of the fault at tunnel level, the tunnel alignment was moved 50 m to the south of the main fault (Figure 3). Ultimately this re-alignment proved vital to the success of the project, as extremely poor ground conditions were encountered in the re-aligned section peripheral to the main fault. Had the hard rock TBM attempted to pass through the main part of the fault then the impact to the project could have been severe.

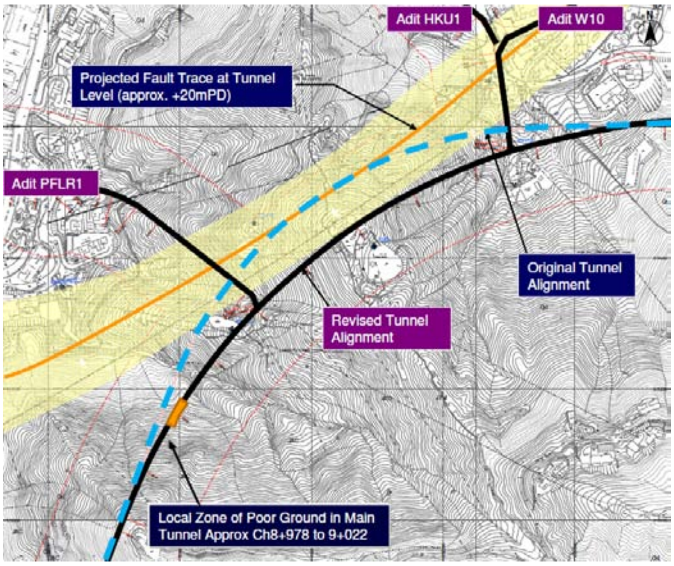

Figure 3: Re-alignment for Sandy Bay Fault

A major geological structure associated with the Sandy Bay Fault was encountered underlying Lung Fu Shan Country Park to the south west of the main fault location. In an approximate 44 m wide zone, Q values dropped to 0.03, in a highly fractured, very blocky, fault breccia with initial groundwater inflows into the tunnel in the region of 100 L/min. Due to the low strength of the rockmass, the tunnel face frequently failed and collapsed into the cutterhead with resultant overbreak around the TBM. The ground squeezed around the TBM which could only be advanced in single shield mode advancing the TBM by pushing off the tunnel lining, as the grippers were experiencing bearing capacity failure in the faulted ground. Planned emergency remedial works were agreed and implemented, as cavity grouting and secondary grouting were implemented. Convergence monitoring was installed confirming the stability of the tunnel lining.

The Telegraph Bay Fault also ran parallel to the tunnel alignment. Although the ground conditions were not as severe as the Sandy Bay Fault, water inflow from probe holes frequently attained over 3.5 L/min/m over an extensive length of tunnel 400 m in length. This necessitated major pre-excavation grouting which commonly attained 20 m^3 to 40 m^3 of grout per 40 m length of grouting cycle and on several occasions between 50 m^3 and 80 m^3 per grouting cycle. In such ground the time spent grouting a full round of grout holes would typically take up to 48 hours which adversely impacted the overall progress of the TBM.

5. GROUND CONDITIONS & TBM PROGRESS

Comparisons have been made on the relative performance of the TBM: the eastern TBM driving in the granites and the western TBM predominantly in volcanic tuff (Table 2). The relatively easier passage of the eastern TBM is highlighted by the fact that only 15 % of the operational time was spent probing ahead and associated grouting, as compared to 26 % for the western TBM.

Table 2: Comparison of production rates (m/day) for eastern and western TBM drives

	Average production rate (Fault zones)	Average production rate (Non-Fault Zones)	Overall production rate
Eastern TBM*	9.24	13.90	13.61
Western TBM**	7.27	10.97	9.86

*Eastern TBM production rates adjusted from 16 hours 6 days per week production cycle.
** Western TBM rates are for 24 hours 7 days per week production cycle.

In total, 703m (18.7 %) of the eastern TBM drive required ground treatment for water ingress compared to 1,800m (27.6 %) for the western TBM. The ground treatment for the respective tunnels are summarized in Table 3.

Table 3: Ground treatment summary for eastern and western TBM drives

	Number of probe cycles	Length of probes (m)	Number of grout holes	Length of grout holes (m)	Total volume of grout (m^3)
Eastern TBM	103	5,591	101	4,617	331
Western TBM	210	12,280	472	24,258	1,438

6. CONCLUSIONS

The HKWDT will meet a major social and business need by alleviating flooding problems in the densely urbanized residential and commercial areas of northern HK Island. The entire drainage tunnel system comprises over 21 km of interconnected tunnels, adits and dropshafts. The main tunnel was excavated by two hard rock double-shield TBM's with excavation diameters of 7.2 m for the eastern TBM tunnel and 8.2 m for the western TBM tunnel. The eastern TBM excavation was largely in granites and passed through two major faults, viz the Tai Tam Fault and Wong Nai Chung Gap Fault. Although fault breccia and fractured ground was encountered, water inflows into the tunnel were not severe and therefore managed through the normal pre-treatment grouting cycle. The western TBM excavation in volcanic tuffs and to a lesser extent granites, experienced more difficult ground conditions, both extremely strong vitric tuff with unconfined compressive strength up to 353 MPa and also severely faulted ground with significant groundwater inflows, associated with the parallel alignments of the Telegraph Bay Fault and Sandy Bay Fault systems. Systematic pre-treatment of the ground up to 40 m in advance of the excavation face was required using combinations of micro-fine cement grout and 2 % micro silica. Comparison is provided for the east and west TBM's in terms of cutting time, probing and grouting time relating to the ground conditions.

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