The Integrated Delivery of a Major Urban Tunnelling Project: Hong Kong West Drainage Tunnel

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ABSTRACT

The Hong Kong West Drainage Tunnel (HKWDT) meets a major social and business need, by preventing flood damage to the most densely urbanized areas of Hong Kong (HK) Island. The 10.7 km drainage tunnel is the longest in HK, and has a large excavated diameter of up to 8.2m. The main tunnel is connected to over 8 km of horizontal branch adits, which link to vertical dropshafts that intercept the existing stream courses and culverts, where separate intake structures have been constructed. This project is the first one to systematically use the raise boring method to excavate dropshafts in HK to reduce the need for spoil removal at the surface onto narrow congested roads. Adit excavation was integrated with TBM excavation concurrently, whereby protocols were developed to enable TBM works to continue in close proximity to blasting works with minimum interference. This paper discusses all significant challenges in managing the quality and safety of the project.

1. PROJECT BACKGROUND

The Hong Kong West Drainage tunnel (HKWDT) meets a major social and business need by preventing flood damage to the densely urbanized residential and commercial areas of northern Hong Kong (HK) Island. Most of the existing drainage systems in the lower catchment of northern HK Island were built more than 50 years ago and can no longer cope with the increased runoff resulting from rapid urbanization. In recent years flooding in rainy season has caused severe disruption to the urban environment.

Figure 1 Flooding in the urban area during a rainstorm

The Drainage Services Department of Hong Kong Special Administrative Region Government (DSD), opted for an *interception approach* to divert storm flows from major watercourses and convey the intercepted flow via a tunnel system to the sea. The possibility of major improvement to the lower drainage catchment was ruled out on account of many constraints in the heart of the urban area.

The general alignment of the main tunnel commences at Tai Hang in the centre of HK Island and discharges 10.7 km away at the outfall located at Cyberport on the south-west coast of HK Island.

Intakes

Tunnel / Adit Alignment

Figure 2 Hong Kong West Drainage Tunnel

The drainage tunnel is the longest in HK and has two excavation diameters of 8.2m downstream and 7.2m upstream. The main tunnel branches into over 8km of 2.8m diameter horse shoe shaped horizontal adits, which link to vertical drop shafts up to 180m deep. The top of the dropshafts intake structures intercept the existing stream courses and culverts.

The whole system is capable of discharging a 200 year storm event, 135m^3/s of water at peak flow to a large outfall structure on the coast.

Ove Arup & Partners HK Limited (Arup) were commissioned by DSD in March 2006 to undertake the design, tender and construction supervision of HKWDT. The construction commenced in November 2007. The project is now near completion and will be commissioned in 2012.

2. DESIGN PLANNING AND DELIVERABLES

HKWDT is a design and build project, with the Contractor having the detailed design role, but with the Employer retaining responsibility for hydraulic design of the tunnel system and also programme-critical items such as the design of both tunnel portals, which enabled the Contractor to start construction at the earliest opportunity on site with statutory design approvals already in place.

To facilitate the tight programme and overall progress of the design, Arup undertook extensive engineering, hydraulic and environmental assessments, which detailed the design standards, philosophy and criteria to be adopted for the design of the Project.

The following core deliverables were prepared for the Employer:

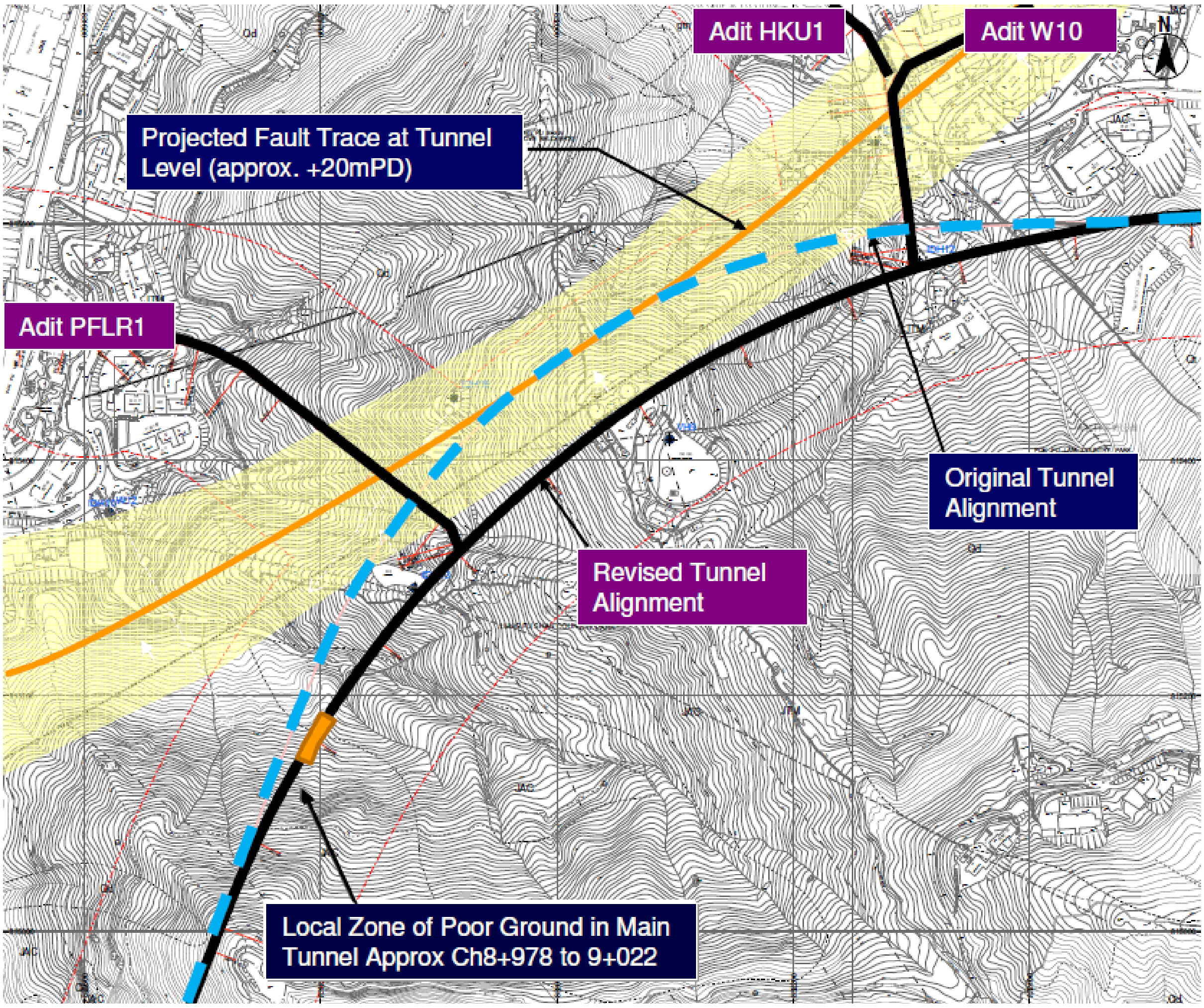
(a) Reference Scheme Design: Tunnel and Adit Alignments and Levels
(b) Hydraulic Design
    i. Physical Model Testing of Intakes
(c) Structural Design
    i. Reference Design of Lining for Main Tunnel, Adits and Dropshafts
(d) Geotechnical Design
    i. Geotechnical Interpretative Report
    ii. Settlement and Ground Movement Report (SGMR)
    iii. Submission for Proposed Works in the Mid-Levels Scheduled Area
    iv. Revised Tunnel Alignment in Sandy Bay Fault Zone
    v. Detailed Design of Permanent Slope Works
    vi. Reference Design for Permanent Slope Works
(e) Blasting Assessment
    i. Blasting Assessment Report (BAR)
(f) Aesthetic and Landscape Design
(g) Environmental Report
(h) Construction Feasibility
    i. Proposal for Concurrent TBM Excavation and Blasting
(i) Operation and Maintenance: Draft Manual

3. TUNNEL ALIGNMENT

The basic philosophy of the horizontal tunnel alignment was to pass beneath the southern fringe of the Mid-Levels urban area, starting from the Eastern Portal at Tai Hang Road running west to Cyberport on the south-west coast. To prevent any land acquisition difficulties it was decided at an early stage to avoid passing under private land. Instead, the entire scheme underlies Government land. The alignment aimed to strike a balance between minimizing the length of the main TBM tunnel drives and the adits constructed by drill and blast methods.

The vertical alignment of the main tunnel is constrained by the elevations of the Eastern Portal (+48mPD) and the Western Portal (+3mPD), and the elevation of the existing Aberdeen Tunnel which has a separation distance of 8.5m. The main tunnel has a gradient of approximately 1/364 for the section to the east of the Aberdeen Tunnel and then a gradient of approximately 1/203 for the section to the west of the Aberdeen Tunnel. The average depth of the tunnel is approximately 225m below ground with a maximum depth of approximately 320m.

Additional ground investigation was undertaken in the area of the Sandy Bay Fault, where it was found that the proposed alignment crossed and then ran parallel with the main fault. The structural geology was reviewed in detail and the tunnel re-aligned 50m south of the main fault. 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 tried to pass through the main part of the fault then the impact to the project would have been severe.



- *Considering orientation and dip of Fault, a realignment of up to 50m to the southeast was recommended.*
- *Zone of poor rockmass approx. 44m long encountered in the main tunnel on cross fault of main Sandy Bay Fault.*

Figure 3 Sandy Bay Fault – Original and Revised Alignment of Main Tunnel

The Eastern Portal TBM launch site was extremely small (approximately 600m^2) and bounded by a busy public road, historic building and a large secondary school. An initial 60m straight section of tunnel was introduced to enable a launch chamber to be excavated. It was further envisaged that this section of tunnel would be used to house a permanent Maintenance Chamber and Intake Chamber.

To accommodate the 60m straight section of tunnel a minimum 300m radius curve was introduced. This standardized minimum radius enabled standard features on both TBM's and rationalised segmental lining design to give further economies of scale in segment casting.

Figure 4 Eastern Portal TBM launch site bounded by busy public road, historic building and large secondary school (left); and Eastern Portal TBM launch chamber (right)

4. HYDRAULIC PERFORMANCE

Arup assessed hydraulic performance of the main tunnel and adits using an InfoWorks CS Model in accordance with the guidelines contained in the Stormwater Drainage Manual (SDM) published by DSD. The design 200-year storm event was modelled to ensure that a free surface be maintained throughout the main tunnel which was the main sizing criteria.

Under the supervision of Arup scale physical models were constructed to model the hydraulic performance of lateral inflow structures and bottom rack structures. The objective of the study was to investigate the shape and impact of blockages on the performance of the bottom rack structure components and to determine the optimal design.

Figure 5 Physical Model Testing used to assess hydraulic performance of Intakes

5. ALLOWABLE SEEPAGE AND SURFACE SETTLEMENT

With up to 320m of cover and the possibility of high water pressures, gaskets could not be guaranteed to provide an undrained tunnel. It was therefore decided to opt for a drained tunnel, but this approach needed robust safeguards to protect the urban area from ground water drawdown and surface settlement, which could have potentially catastrophic consequence given the very high real estate values in HK.

To facilitate the specification of adequate but achievable allowable groundwater inflow criteria Arup prepared a Settlement Ground Movement Report (SGMR) based on hydro-geological modelling. This presented the predicted ground settlement due to groundwater drawdown during construction and the assessment of the effect of the ground settlement on the adjacent existing buildings, structures and utilities.

Based on allowable settlements at the surface, allowable groundwater drawdown and inflows into the tunnel were predicted. Advanced probing ahead of the TBM was specified throughout.

The allowable infiltration into the tunnel during construction was specified not to exceed any of the following limits,

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

Pre-excavation grouting was carried out by pumping micro-fine cement grout 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. If water inflow exceeded the infiltration requirements from the additional probe hole, further grouting was carried out. For zones of high ground water inflow, up to 2% micro-silica was added to the micro-fine cement ensuring that the infiltration limits were achieved. During the grouting operation skilled operatives closely monitored the actual site situation and reviewed the performance of the grouting works to choose the most suitable grout material for the treatment of the observed ground condition.

Furthermore it was specified in the Employer's Requirements that the Contractor would prepare an Existing Building and Structure (EBS) Condition Survey, Preliminary and Detailed Construction Risk Assessment (CRA) to demonstrate that the works would not induce unacceptable damage to the EBS. As an added safeguard regional settlement monitoring of structures was undertaken using Persistent Scatter Interferometric Synthetic Aperture Radar (PSInSAR).

6. ASSESSMENT of CONSTRUCTION FEASIBILITY

6.1 Tunnel Boring Machine (TBM) allocation

Early in the planning stage a study of the construction programme and sensitivity to delay was undertaken to assess the viability of using a single TBM, instead of 2 TBM’s. It was concluded that a single TBM construction operating from the Western Portal could not complete the excavation within the required 49 months construction period. The expected contract over-run caused by using a single TBM would have been approximately 12 to 14 months. The consequence of this decision was that it was necessary to launch the second

TBM from an extremely confined site at the Eastern Portal. Ultimately this proved to be the correct decision as the West and East TBM's achieved 10.2 months and 8.1 months respectively, close to what was assumed in the in earlier study.

6.2 Geology and TBM type

Based on the ground investigation data and geotechnical studies it was anticipated that the tunnel would run through competent granite and tuff, however, 30 potential faults zones were also identified of which 8 were classified as major faults and likely to exhibit poor ground conditions.

The need to pass through highly fractured rock where TBM gripper anchorage could be difficult led to the decision to specify double shield TBM's which can advance forwards using the thrust cylinders pushing off the installed lining. A double shield TBM can be advanced concurrently with the ring building, without any interruptions in the normal operation.

Poor ground conditions were encountered in the Sandy Bay Fault and the grippers failed to provide adequate anchorage in the weak ground. The flexible design allowed the TBM to switch to single shield mode and push of the installed lining with the thrust cylinders.

The materials excavated by the TBM's were transported from the face to the back of the TBM gantries by conveyor and then by long wall conveyor to the tunnel portal. All materials from the West TBM were directly transferred from the conveyor onto barges for beneficial reuse by other construction projects.

6.3 Preliminary Blasting Assessment Reports

With 8km of adit to excavate, blasting formed a major component of the project and required careful planning and collaboration with interested parties. The northern sections of most adits underlie the urban area with as little as 20m of cover. Many sensitive receivers are located above the adits, including 650 slopes and retaining walls, numerous buildings and utilities.

Prior to construction Arup prepared Blasting Assessment Reports (BAR's) to review the viability and generally assess the best approach and consequences of blasting. The reports identified safe peak particle velocity (ppv), best methods of excavation and explored the various blasting constraints and requirements intended to make the blasting safe.

The preliminary BAR's were agreed with the regulator Mines Division of Civil Engineering and Development Department to demonstrate that the blasting arrangements would be feasible. However flexibility was left such that the Contractor could identify the final blasting measures and submit them for approval with the blasting permits and application for a blasting license. The two stage approach with Arup preparing the initial BAR's which were then developed by the Contractor was the most effective way to stream line the approval process and minimize the potential for later unforeseen problems.

At peak production adit excavation involved blasting up to ten adits per day, some of which had two blasts and the concurrent operation of the TBM. This was a major logistical challenge for the typical operational blasting cycle of drilling, charging, blasting and mucking out. All explosives going into the tunnels and excavated material transported out had to pass through one of the two tunnel portals putting severe strain on the rail system and general logistical operation.

6.4 Concurrent operation of TBM's and adit blasting

Historical practices in HK had dictated that all tunnel workers be evacuated from the underground space during charging, initiation, mis-fire identification and blast fume venting. It was realized at an early stage that if the TBM crews had to be evacuated from such long TBM tunnels each time a blast occurred in the 32 adits, then the progress of the TBM tunnels and the overall projects would be severely affected.

To address this issue Arup prepared a working paper titled "Proposal for Concurrent Tunnel Boring Machine (TBM) Excavation and Adit Blasting" which was used to facilitate discussion and agreement between the statutory authorities that TBM workers could remain underground in purpose built evacuation chambers during blasting activities. Agreement was reached and provisions were inserted into the Employer's Requirements that subject to the performance of satisfactory trials during the construction phase then concurrent operations would be allowed.

A series of trials were successfully performed demonstrating the safety of the concurrent operations, which have made a major contribution to the progress of the works.

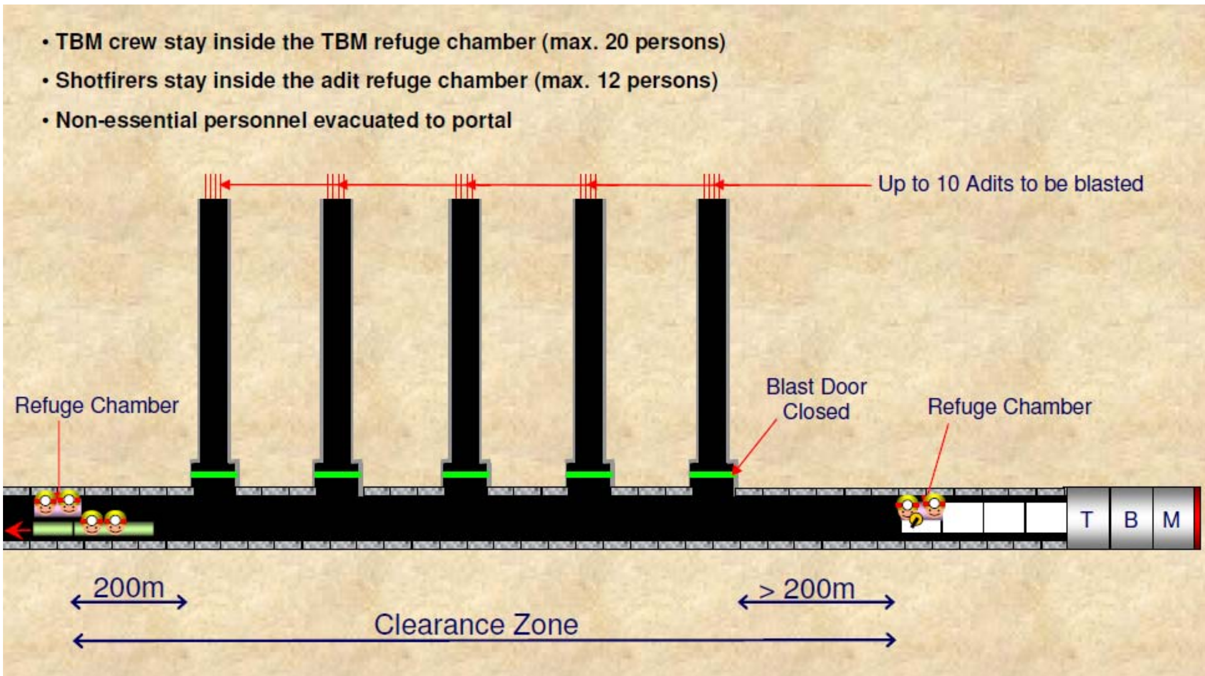


Figure 6 Concurrent blasting of adits and TBM operation – Evacuation Protocol

Figure 7 Refuge Chamber for tunnel workers during concurrent blasting

6.5 The advantages of raise boring

The project required the excavation of 31 vertical dropshafts up to 168m depth ranging in diameter from 1.5m to 2.3m. No such project had ever been undertaken in Hong Kong and therefore possible construction methods had to be closely studied by Arup. Main factors were the ground conditions and the confined urban nature of many of the sites located between buildings with stringent statutory requirements in terms of traffic control, vehicular access and general consideration to the local inhabitants.

The study concluded that raise boring was the optimal method to excavate 23 of the 31 dropshafts. This had the major advantage over other methods that spoil did not need to be removed at the top of the shaft, instead it could be removed from the base of the shaft using the spoil handling system already in place for adit and tunnel excavation. The number of dump trucks traversing the congested streets of the Mid levels were thus vastly reduced.

The same considerations for allowable seepage and surface settlement were applied to the dropshafts. The Contractor pre-drilled all shaft locations and devised a pre grouting regime predicted to control seepage and stability during drilling and reaming. This proved to be highly successful.

Four raise boring machines were mobilized from Australia. Raise boring involved drilling a 300 mm diameter pilot hole from the ground surface down into the excavated stilling chamber located at the end of the adit. To maintain verticality of the pilot hole and subsequent shaft this called for very careful set-up of the raise bore rig and careful drilling and reaming. Once the pilot hole was through into the stilling chamber the reaming head was installed and reaming could commence.

Typical progress rates for a 10 hour working day were: pilot hole drilling in the range 6m to 10m per day and for reaming 3m to 4m per day all depending on depth and rock quality. The shaft reaming rates were significantly faster than what could have been achieved by other methods such as hand dug caisson and conventional piling methods such as reverse circulation drilling. Considering the programme, environmental and small working space requirements the choice of raise boring method was of major benefit to the project.

Figure 8 Raise boring equipment setup at Intake location

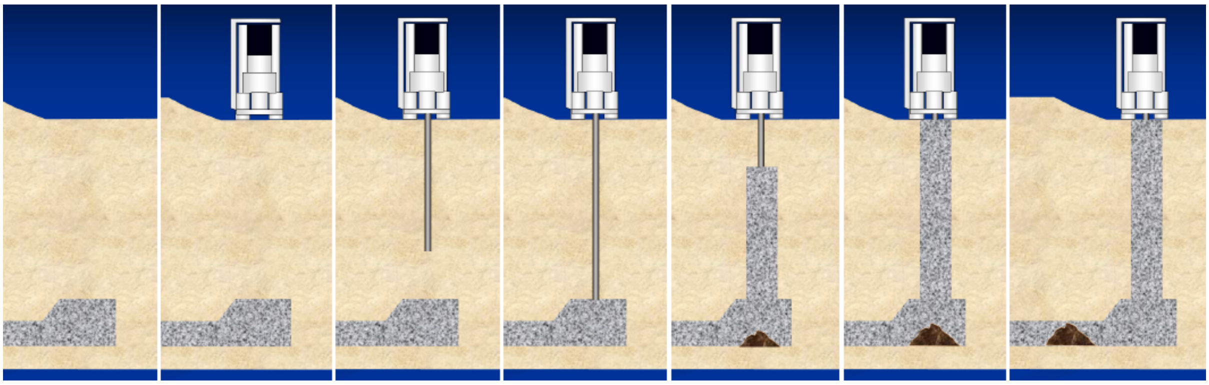


Figure 9 Raise boring operation - pilot hole drilling, reaming & spoil removal via adit & tunnel

7. CONCLUSIONS

The HKWDT meets a major social and business need by preventing flood damage to the densely urbanized residential and commercial areas of northern HK Island. The drainage tunnel is the longest in HK and has two excavation diameters of 8.2m downstream and 7.2m upstream. The main tunnel branches into over 8km of 2.8m diameter horse shoe shaped horizontal adits, which link to vertical drop shafts up to 180m deep. The whole system is capable of discharging a 200 year storm event, $135m^3/s$ of water at peak flow to a large outfall structure on the coast.

Arup undertook extensive engineering, hydraulic and environmental assessments, which detailed the design standards, philosophy and criteria to be adopted for the design of the Project. Arup assessed hydraulic performance of the main tunnel and adits.

The need to pass through highly fractured rock where TBM gripper anchorage could be difficult led to the decision to specify double shield TBM's which can advance forwards using the thrust cylinders pushing off the installed lining. A double shield TBM can be advanced concurrently with the ring building, without any interruptions in the normal operation.

Provisions were included in the Contract for TBM workers to remain underground in purpose built evacuation chambers during blasting activities, subject to the performance of satisfactory trials during the construction phase.

Raise boring had the major advantage over other methods that spoil did not need to be removed at the top of the shaft, instead it could be removed from the base of the shaft using the spoil handling system already in place for adit and tunnel excavation. The shaft reaming rates were significantly faster than what could have been achieved by other methods such as hand dug caisson and conventional piling methods such as reverse circulation drilling. Considering the programme, environmental and small working space requirements the choice of raise boring method was of major benefit to the project.